VELOCIMETERS

Velocimeters are instruments used to measure the speed of a moving object or medium. Velocity is a vector quantity; that is, it has both magnitude (commonly referred to as speed) and direction. Many devices classified as velocimeters only measure the magnitude of the motion or its speed; the direction of the motion is known a priori or must be assumed. Speed is an important quantity in many situations. We may want to know the speed of an automobile, the rate of expansion of the universe, or the flow profile in a blood vessel in the heart. Because velocity and volume flow rates are directly related, some of the techniques described in this article might also be classified as flow meters. One specific category of flow meters is anemometers—devices for measuring the speed of gases, usually air.

A transducer is a device used to convert a physical measurand or variable, such as speed, into a signal in an alternate energy form. For our purposes, this is usually an electrical signal, but it could be a mechanical deflection in a direct reading gauge, for example. The electrical parameter that varies with the measurand can be voltage, current, frequency, or phase. The electrical signal may be directly generated, as in electromagnetic induction, or it may arise from modulation, as in the change of resistance in hot-wire anemometry.

For a linear or translational frame of reference, the following definitions and relationships exist. Displacement, x, is the change in position. Velocity, v, is the rate of change of position. Acceleration, a, is the rate of change of velocity. These can be expressed mathematically by the following differential equations:

$$v(t) = \frac{d}{dt}x(t) \quad \text{and}$$
$$a(t) = \frac{d}{dt}v(t)$$

A similar set of relations exists in an angular or rotational frame of reference.

$$\omega(t) = \frac{d}{dt}\theta(t) \quad \text{and}$$
$$\alpha(t) = \frac{d}{dt}\omega(t)$$

where θ is the angular displacement, ω is the angular velocity, and α is the angular acceleration. From this, we can see that if we can measure displacement or acceleration then we can calculate velocity. However, the signal processing may introduce additional sources of error. In particular, differentiation will tend to enhance any high-frequency noise present in the displacement signal. On the other hand, an offset error or low-frequency drift in the zero level of the acceleration signal will cause errors in the integration process. The use of digital computers has greatly facilitated signal processing and has reduced the sources of errors that can corrupt the velocity signal. However, both high-frequency noise and offset or drift can occur in the analog electronics required for most transducers prior to the signal being digitized.

PHYSICAL PRINCIPLES OF DIRECT VELOCITY MEASUREMENT

As mentioned previously, several physical phenomena can be made to depend directly on the speed of a moving object or fluid. These include electromagnetic induction, the Hall effect, and several variations of the Doppler effect.

Electromagnetic Induction

Electromagnetic induction and the Hall effect (see the next subsection) have the same physical basis—namely, that an electric charge moving through a magnetic field undergoes a lateral force known as the Lorentz force. Michael Faraday first described the phenomenon of electromagnetic induction that has become familiar to electrical engineers through the mathematical relationship referred to as Faraday's law of induction. That is, a voltage will be induced across the windings of a coil that is proportional to the rate of change of flux linkages, λ, in the coil. The polarity of the voltage will be such that if a current can flow it will tend to oppose the change in flux; hence, the minus sign in Eq. (1):

$$e = -\frac{d}{dt}(\lambda) \tag{1}$$

and

$$\lambda = n\phi$$

where n is the number of turns linked with the flux and ϕ is the magnetic flux. If the number of turns linked with the flux is fixed, then a more familiar form of Faraday's law results:

$$e = N\frac{d}{dt}\phi(t) \tag{2}$$

The flux, ϕ, can be represented more usefully as

$$\phi = BA$$

where B is the flux density and A is the cross-sectional area of the coil exposed to the magnetic field. Velocity transducers based on electromagnetic induction have a coil that moves with respect to a magnetic field such that the rate of change of flux linkages is proportional to the velocity. Two possibilities, a moving coil or a moving core, are shown in Fig. 1.

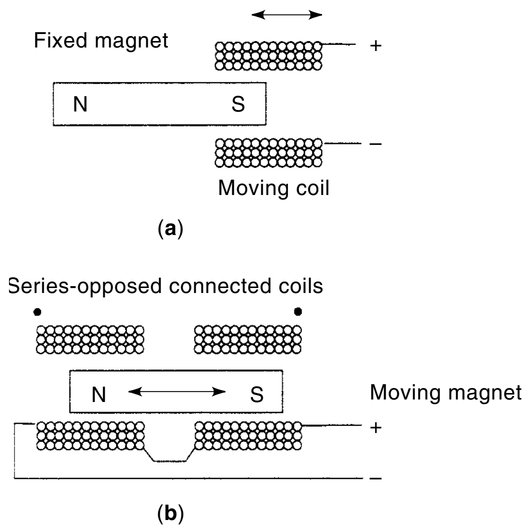

Figure 1. Electromagnetic induction of an electrical potential difference by changing the number of turns linked with the flux. (a) Moving coil and a stationary magnet, (b) two coils connected in series opposition with a moving magnet in the lumen of the coil.

If a single rectangular loop under motion is only partially within the magnetic field (Fig. 2), then Eq. (2) can be restated as

$$e = \frac{d}{dt}BA(t)$$

since $N = 1$.

The area exposed to the magnetic field is the lx, where l is fixed and x changes due to being linked to the system being measured. Then

$$e = \frac{d}{dt}Blx(t)$$
$$\Rightarrow e = Bl\frac{dx(t)}{dt}$$
$$\Rightarrow e = Blv$$

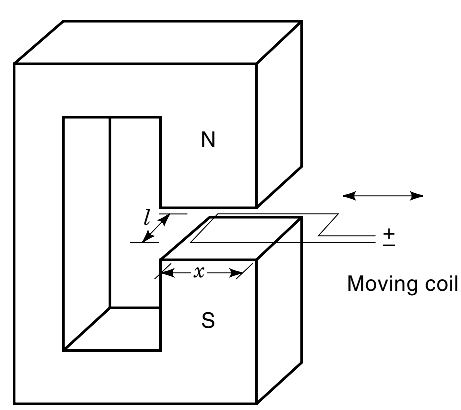

Figure 2. Electromagnetic induction of an electrical potential difference by changing the area of a coil exposed to a magnetic field; l is the width of the coil, and x is the length of the coil in the magnetic field.

where the velocity, v, is the time derivative of position, x. Strictly speaking, the voltage induced is due to the vector product of the magnetic field and the velocity of the conductor:

$$\boldsymbol{e} = \boldsymbol{v} \times \boldsymbol{B}l$$

The operator × indicates the vector or cross product.

Hall Effect

Hall effect transducers are based on the same separation of charge due to the Lorentz force, as in electromagnetic induction. However, in Hall effect transducers, a current is made to flow through a stationary conductor that is exposed to a dc magnetic field (see Fig. 3):

$$\boldsymbol{F} = q_0\boldsymbol{v} \times \boldsymbol{B}$$

where $\boldsymbol{F}$ is the force vector, q_0 is the charge, $\boldsymbol{v}$ is the velocity vector of the charge, and $\boldsymbol{B}$ is the magnetic flux density vector. The magnitude of the force is therefore

$$|\boldsymbol{F}| = F = q_0 vB \sin\theta$$

where θ is the angle between the velocity and the magnetic field. Since the electric charges are free to move laterally, the Lorentz force will act to deflect the charges. Then an electrical potential difference will develop perpendicular to the flow path. This potential is referred to as the transverse Hall potential, V_H.

$$V_H \propto iB \sin\theta$$

This principle can also be used in flow meters for ionized solutions in which the flow of ions becomes the current. In this case, the ion concentration and temperature of the solution will also affect the Hall potential as well as the velocity of the fluid.

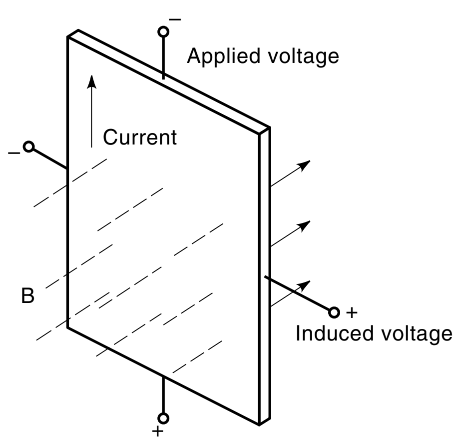

Figure 3. Hall effect principle: An external voltage source is connected across the top and bottom terminals, which causes an electric current to flow. In the presence of a magnetic field (B), the moving charges are displaced laterally due to the Lorentz force. This sets up an induced electrical potential difference (the transverse Hall potential) orthogonal to the current direction and the direction of the magnetic field.

Doppler Effect

The Doppler effect is most commonly observed when a sound source is in motion relative to a receiver. Thus, the engine of a racecar is perceived to have a higher pitch as it approaches a spectator than after it passes the spectator. This can be extended to any source of propagating waves—ultrasound, microwave, and light:

$$f_0 + f_d = f_0 \frac{c}{c + v_s \cos\theta}$$

where f_0 is the frequency of the transmitter, f_d is the frequency shift, v_s is the velocity of the source with respect to the receiver (positive away from the receiver), θ is the angle between the trajectory of the source and the path of propagation between the source and the receiver, and c is the speed of the propagating wave. This formulation assumes a frame of reference relative to the receiver. This is the basis for the "red shift" observed in the photoemissions from stars, which has allowed astronomers to estimate the rate of expansion of the visible universe. In many applications involving Doppler frequency shift, the transmitter and receiver are both stationery, but an intermediary object, referred to as the target, is moving with respect to both. Then two shifts occur: the target with respect to the source and the receiver with respect to the target. If the transmitter and receiver are located in close proximity to each other, then the Doppler shift becomes

$$f_0 + f_d = f_0 \frac{(c + v\cos\theta)}{(c - v\cos\theta)}$$

If $v \ll c$, then this becomes

$$f_d \cong \frac{2f_0 v\cos\theta}{c}$$

Sonic and microwave Doppler velocimeters are usually based on this principle. The object to be measured must have a different impedance than the surrounding medium so that a reflection occurs. For microwave Doppler velocimeters (such as "radar guns"), this is not usually a problem. However, for Doppler flow meters, particles or bubbles must be suspended in the flowing medium in order for a reflected signal to occur. This formulation is applicable if the source is a continuous wave. Pulsed ultrasound flow meters are often referred to as Doppler flow meters. Strictly speaking, however, their principle of operation is time of flight for two successive pulses (1).

Transit Time

The motion of the medium through which the wave propagates can also be used to measure velocity. This does not require any reflective objects in the medium as is required in the Doppler flow method. The length of time taken for a signal to propagate from a transmitter to a receiver depends on the velocity of the medium through which the signal flows. For a more complete development, the reader is referred to Lynnworth (2):

$$T = \frac{D}{c + v_c \cos\theta}$$

where T is the transit time, D is the distance between the source and the receiver, c is the speed of wave propagation, v_c is the average velocity of the medium along the propagation path, and θ is the angle between the flow vector and the propagation path (see Fig. 4). Note that v_c is taken as positive when the transmitted wave is in the downstream direction. Note also that v_c is not the average velocity across the cross section of the flow. The propagation speed also depends on the density and adiabatic compressibility of the medium. These parameters vary with temperature. Usually the transit time is measured in both the upstream and downstream directions, and the time difference is taken. The time difference varies directly with velocity (3).

$$\Delta T = \frac{2Dv_c \cos\theta}{c^2 - v_c^2 \cos^2\theta}$$

For $c \gg v_c$,

$$\Delta T \cong \frac{2Dv_c \cos\theta}{c^2} \tag{3}$$

The distance, L, is the separation of the transmitter and receiver along the flow path (Fig. 4). This parameter may be easier to measure than the actual path length. Equation (3) becomes

$$\Delta T \cong \frac{2Lv_c}{c^2}$$

since

$$D = \frac{L}{\cos\theta}$$

For ultrasonic velocity measurement, the velocity of the fluid is typically less than 1% of the speed of sound. Therefore, the speed of sound must be known to within 0.01% for the velocity to be calculated to within 1%. The speed of sound is dependent on the bulk modulus and the temperature of the conducting medium. Therefore, where either of these variables is not carefully controlled, large errors in the calculated velocities will result from measuring the difference in transit times.

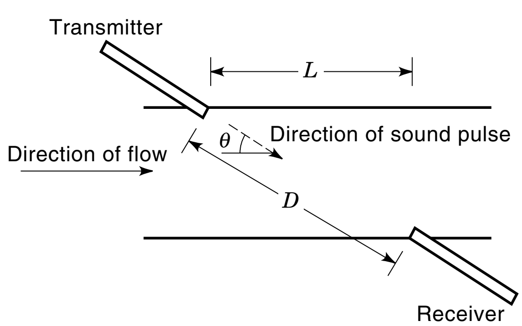

Figure 4. Schematic representation of the measurement of velocity by the transit time of a pulse of sound energy. The fluid is shown flowing in a pipe. The transmitter and receiver are on opposite sides of the pipe at an angle θ to the flow. The transmitter and receiver are separated by a distance L along the pipe and a distance D along the path of the propagated sound.

However, further calculation can be used to remove the speed of wave propagation. The sum of the upstream and downstream transit times is

$$\sum T \cong \frac{2D}{c}$$

Then dividing the time difference by the square of the sum of the transit times gives

$$\frac{\Delta T}{\left(\sum T\right)^2} \cong \frac{v_c \cos\theta}{2D}$$

Now the angle between the flow and wave propagation must be known. Subnanosecond time resolution is required for 1% accuracy for typical measurement situations (2).

An alternative approach is to have the pulse repetition rate inversely proportional to the transit time. Then the difference in frequency between the upstream and downstream pulse trains is

$$\Delta f = \frac{2v_c \cos\theta}{D}$$

or

$$\Delta f = \frac{2v_c}{L}$$

In this formulation, the propagation speed of the wave does not affect the pulse repetition frequency, and only the axial separation of the transmitter and receivers needs to be known. However, for ultrasonic velocity measurement, Δf is expected to be small, which can result in considerable error in the calculated velocity.

The time shift can also be considered as a phase shift with respect to the source oscillator:

$$\Delta\varphi = 2\pi f_o \Delta T$$
$$\Rightarrow \Delta\varphi = \frac{4\pi f_o D v_c \cos\theta}{c^2}$$

where $\Delta\varphi$ is the phase shift, f_o is the oscillator frequency, and all other variables are as defined previously. Phase shifts can be measured optically through interference effects. With the proper choice of materials in the optical path, changes in ambient conditions have a negligible effect on the speed of light, and laser light sources provide a stable frequency (or wavelength). For acoustic velocimeters, variations in the speed of sound introduce errors in calculated velocities, as was the case for transit time. However, phase difference is easier to measure than small time differences. The disadvantage of phase measurement is the ambiguity that results from the periodicity of the phase shift. This restricts the flow range that can be measured. The maximum carrier frequency, f_o, is calculated by setting the preceding equation to π and solving for frequency given the maximum value of velocity to be measured, the separation distance and angle of the two transducers, and the minimum expected speed of sound over the operating temperature range. A standard crystal frequency below this value may then be selected.

Errors due to changes in the speed of sound with temperature can be eliminated by using two frequencies (4). The phase difference is then obtained between the two upstream signals, and a second phase difference is obtained between the two downstream signals:

$$\Delta\phi_1 = \frac{2\pi f_1 D}{c + v_c \cos\theta}$$

and

$$\Delta\phi_2 = \frac{2\pi f_2 D}{c + v_c \cos\theta}$$

where f_1 and f_2 are the two signal frequencies and all other variables are as previously defined. Then

$$\Delta\phi_{\mathrm{u}} = \frac{2\pi (f_2 - f_1) D}{c - |v_c| \cos\theta} \tag{4}$$

and

$$\Delta\phi_{\mathrm{d}} = \frac{2\pi (f_2 - f_1) D}{c + |v_c| \cos\theta} \tag{5}$$

where u and d indicate the upstream and downstream phase shifts, respectively. One of the frequencies, say f_1, is still used to calculate the upstream-downstream phase shift.

$$\Delta\varphi_1 = \frac{4\pi f_1 D v_c \cos\theta}{(c - |v_c| \cos\theta)(c + |v_c| \cos\theta)} \tag{6}$$

Equations (4) and (5) are rearranged and substituted into Eq. (6), and the resulting equation is rearranged to give

$$v_c \cos\theta = \frac{\pi (f_2 - f_1)^2 D \Delta\varphi_1}{f_1 \Delta\phi_{\mathrm{u}} \Delta\phi_{\mathrm{d}}}$$

In this way, the calculation of flow velocity does not depend on the speed of wave propagation. As mentioned previously, stable oscillators are readily available, and phase differences can be measured relatively easily. A second calculation of the flow velocity can also be made using the second frequency upstream-downstream phase shift. Then the average of these two values can be taken, which provides some reduction in the error. The frequency, f_1, is calculated as for the single-frequency method. The maximum difference between the two frequencies is found by taking the difference of the upstream and downstream phase shifts [Eqs. (4) and (5)] and setting the difference equal to π. In this case, the minimum expected speed of sound is used for the upstream phase shift, and the maximum expected speed of sound is used for the downstream phase shift. The second frequency, f_2, is then chosen as a standard crystal frequency above that of f_1 but less than the calculated difference.

PHYSICAL PRINCIPLES OF INDIRECT MEASUREMENTS

As mentioned previously, velocity can be determined from successive measurements of position. Many displacement transducers are based on variable resistance, capacitance, inductance, or reluctance. Differentiation of an electrical signal that is modulated by the change of one of these parameters is a straightforward process. Only those displacement techniques developed specifically for use with velocimeters and anemometers will be discussed here. Time is a parameter that can be measured with good accuracy and resolution. Therefore, it is not surprising that measurement of time is the basis for two of these indirect approaches—namely, the time to travel a known distance and the time of flight of two successive pulses of a signal. A related technique is to measure the displacement before and after a known time interval. A third principle is that thermal convection is dependent on mass flow rate, from which velocity can be derived. This is the basis of hot-wire and hot-film anemometry.

Time-Based Techniques

One of the most obvious ways of measuring the average speed of an object is to measure the time it takes to travel a known distance. The transducer for detecting the presence of the object as it passes the start and end points is the major consideration in developing a velocimeter based on this technique. Usually, it is preferable to have a nonintrusive method for detecting the object. Photoelectric timers use a light source (visible or infrared) aligned with a photodetector across the path of the object. These transducers can be readily adapted to a number of applications, including industrial processes and sports activities. Contact switches are another rugged transducer that can be made in a number of form factors and for different environments, such as measuring the speed of automobiles. Because timers and counters can be made with high accuracy and resolution relative to the speed of most large objects, the largest sources of error in such systems are the transduction process and measuring the separation distance of the two position detectors.

Surface texture correlation is a more sophisticated method of determining the time required to travel a known distance. In this technique, two light sources, usually laser beams, illuminate a portion of the surface of a moving object, such as steel or aluminum in a rolling mill or paper, wire, or cable as they are being metered onto rolls. The two beams are a fixed and known distance apart; they are aligned so that the same part of the material passes underneath both beams (Fig. 5). Two photoreceptors provide an analog signal of the light reflected from the two illuminated spots. Differences in surface texture or reflectance will cause variations in these signals. After the signals are digitized and buffered, crosscorrelation is performed on the two signal sequences to find the time lag required to create the largest match between the two signals. Theoretically, if the spots illuminated the same strip of material that passes under both, then the second signal will be a delayed version of the first. In practice, of course, the match is not identical due to differences in photoreceptor response and the presence of noise. High-speed, digital signal processing microprocessors have made this technique feasible for not only monitoring velocity but also, through digital integration, determining the total length of material. Accuracy of better than 0.1% is obtainable. This technique has the advantage of being a noncontact process in which the standoff distance may be more than 0.5 m. Unlike Doppler and transit time techniques, the method is not sensitive to the angle of the beams relative to the material motion, as long as the distance

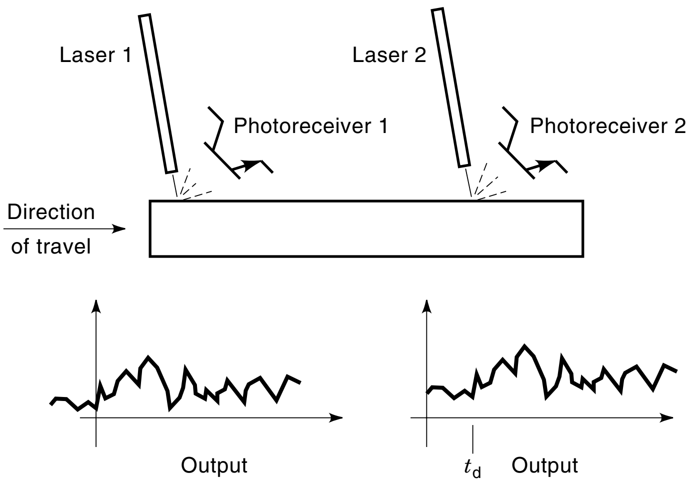

Figure 5. Surface texture correlation. The output of the second photoreceiver is ideally identical to that of the first photoreceiver, but delayed by an amount t_d that is proportional to the separation distance of the two photoreceivers and the speed of the material.

between the two beams on the material surface remains constant.

For time-of-flight measurements, a transmitter emits a pulsed wave that propagates at a known speed. The pulse is reflected off the object of interest (target), and the reflected pulse is received by a detector mounted immediately adjacent to the transmitter. (In the case of ultrasonic time of flight, the transducer can be both the transmitter and the receiver.) The time taken to travel from the transmitter to the detector is proportional to twice the distance from the transmitter to the target. Then successive time measurements allow the calculation of the change in position, and the velocity can be calculated given the interval between pulses:

$$v \cos\theta = \frac{c\Delta t}{2PRI}$$

where v is the velocity, θ is the angle between the path of the target and the path of the propagating pulse, c is the speed of propagation of the pulse, Δt is the difference in the time of flight of two successive pulses, and *PRI* is the pulse repetition interval. This is the technique used in optical radar guns, or lidar.

In pulsed Doppler ultrasound, the reflected pulse can be demodulated by being mixed with a phase-shifted version of the original pulse (1). The phase shift of the original pulse controls the sample depth at which the velocity will be measured. After demodulation and filtering, the phase of the resulting low-frequency signal is proportional to the velocity of a single target:

$$\phi = \frac{4\pi K v \cos\theta}{c}$$

where ϕ is the phase and K is a multiple of *PRI*. Rather than using demodulation, direct sampling of the high-frequency return signal is also possible at a fixed time with respect to the time of pulse emission. If the pulse repetition rate is sufficiently high with respect to the velocity of the target and if a large number of pulse echoes are sampled, then the frequency of the sampled return signal will be proportional to the velocity of the target:

$$f_p = \frac{2 f_0 v \cos\theta}{c}$$

where f_p is the frequency of the sampled return signal and f_0 is the frequency of the ultrasonic wave in the pulse. If the pulse is reflected off multiple objects, as is the case for red blood cells, then the signal processing becomes more complicated, and a frequency spectrum results.

Displacement-Based Techniques

A wide variety of displacement transducers has been manufactured based on changes in resistance, capacitance, reluctance, or inductance. Any of these could be used for velocimeters by differentiating the displacement signal with respect to time. Such transducers will not be discussed here. However, shaft encoders are used in an important category of velocimeters—namely, vane anemometers—as well as being used more generally for any shaft angular velocity measurement. A shaft encoder is one of the few transducers that directly outputs a signal in digital form. Shaft (or linear) encoders come in two types: incremental and absolute. Incremental encoders can be further subdivided into single channel and two channel. The latter have two tracks of encoding bits offset by 90° of the mechanical pitch. Two digital signals are thus generated in quadrature. This allows bidirectional information to be obtained, as well as quadrupling the angular resolution of the encoder. Shaft encoders make use of proximity detectors to determine incremental changes in shaft rotation. This can be done by optical transmission through a disc with alternating opaque and transparent windows, with ferromagnetic gears and a variable reluctance or magnetoresistive transducer that "counts" the gear teeth (5), or with a conductive gear and an eddy-current device. A variation of this technique is to use a reflective target mounted on the shaft of a rotating machine. A photodetector then emits a pulse for each rotation, and the pulses are counted for a fixed duration of time.

Vane anemometers always rotate in the same direction and the absolute angular position is not required; therefore, single-channel incremental shaft encoders are well suited to this application. The angular velocity, ω, can be determined by counting the output pulses for a fixed interval of time. Then the sensitivity of the anemometer is determined by the number of pulses per revolution, N, and the counting interval, T. The range of the anemometer is determined by the size of the counter.

$$\omega = \frac{\text{count}}{NT}$$

Long stroke length (>1 m) linear displacement transducers are difficult to manufacture. Converting the linear displacement to angular displacement is often used for such measurements. This technique is used with cable extension-type displacement transducers. In these transducers, a light, stainless steel line is wound on a reel with a spring return. The shaft of the reel may be connected via a gear train to a potentiometer for an analog output or a two-channel incremental shaft encoder for a digital output (6). These devices are often the transducer of choice for measurements requiring long stroke length (up to 19 m) (7). Some models are available that have a dc tachometer built into the transducer, so that the output is directly proportional to velocity. Typical sensitivities are 30 to 130 $mV \cdot m^{-1} \cdot min$.

A change in displacement can also be measured from successive images of a moving object or fluid field. This is the basis for high-speed cinematography or video recording and for particle velocimeters. High-speed cinematography requires manual digitization of limb or body centroid positions and joint positions on a frame-by-frame basis. Prior to the development of video recordings, there were no effective means of doing this automatically. Video cameras with high frame rates can replace photographic film to capture the images. This lends itself to digitization of the image and subsequent automatic or human-assisted determination of the position of anatomical landmarks. The advantage of cinematography for biomechanical studies is that the positions of individual limbs as well as the whole body can be determined. Thus, forces acting around joints can be calculated from the velocities. However, it is very difficult to acquire images for motions in three dimensions; thus errors are introduced since the velocity vectors are assumed to always lie in the plane of the two-dimensional image. Some systems [e.g., SelSpot II (Selective Electronics, Partille, Sweden)] with markers placed on the body have been developed in an attempt to overcome this limitation.

Particle image velocimeters take successive images of particles in a fluid field. Then two-dimensional correlation is used to find the displacement of greatest match of particle position between the two images. Any motion out of the plane of the image can introduce substantial error in subsequent velocity calculations (8). Various techniques have been used to acquire the two images. The time interval between exposures is usually less than 100 μs in order to get reliable estimates of high-speed irregular flow profiles. Mechanical shutters and mechanical film advancing are too slow for such short interexposure timing. Pulsed lasers are frequently used as a stroboscopic light source to create two images at short time intervals. The image may be a double exposure on a single sheet of film or charge coupled device (CCD) camera. In this case, autocorrelation is used to find the position of the second largest peak, which represents the location of the shifted particles. To determine a complicated flow profile over a large image area, the correlation must be done in subregions of the image. The peaks of interest represent the average shift in particle position within that region.

Autocorrelation results in two such peaks, as there is 180° directional ambiguity in the correlation process. Crosscorrelation of two independent images does not have this ambiguity. However, this requires two independent images, which is a technically challenging proposition. Two exposures at different optical wavelengths can be used to create two separable images, or high-speed liquid crystal shutters can be used to create two images on different halves of a single photographic negative (9).

Acceleration-Based Techniques

In a manner analogous to displacement-based velocimeters, it is possible to create a velocity proportional signal by integrating the output of any accelerometer. In the field of vibration measurement on rotating machines, displacement, velocity, or acceleration may be the preferred parameter to measure. The lowest vibration frequency of interest is usually determined by the angular velocity of the rotating machine. For machines rotating at less than 500 rpm, displacement is usually the preferred measurement because of the frequency response of seismic vibration velocimeters (see the section title in "Linear Electromagnetic Induction Velocimeters") is limited to >5 Hz. For vibration frequencies above approximately 1 kHz, acceleration is usually the preferred measurand. In the midrange (5 Hz to 1 kHz), velocity used to be the preferred measurand using seismic velocimeters. With the development of piezoelectric accelerometers, the practical lower limit for acceleration measurement is now as low as for electromagnetic seismic velocimeters. However, because of the historical use of seismic velocimeters in the midfrequency range, some manufacturers [e.g., (10) and (11)] build velocity sensors based on piezoelectric accelerometers that have an integrator built into the transducer package.

Thermal Convection

Hot-wire anemometry is based on convective heat transfer from a (usually) cylindrical heated wire to a flowing medium. That is, the rate of heat transfer will depend on the fluid's mass flow rate, which is, of course, dependent on the velocity of the fluid. The probes can also be made by depositing a thin film of resistive material on a substrate. This allows shapes other than cylinders to be readily manufactured. These are referred to as hot-film probes. Hot-wire probes can be operated in either a constant temperature mode or a constant current mode. The latter is usually used for measuring temperature rather than mass flow rate. The reader is referred to H. H. Bruun (10) for a full development of the behavior of hot-wire probes.

For a finite length of hot wire,

$$d\dot{Q}_{\mathrm{e}} = d\dot{Q}_{\mathrm{fc}} + d\dot{Q}_{\mathrm{c}} + d\dot{Q}_{\mathrm{r}} + d\dot{Q}_{\mathrm{s}}$$

where $\dot{Q}_{\mathrm{e}}$ is the electrical heat generation rate, $\dot{Q}_{\mathrm{fc}}$ is the forced convective heat transfer rate, $\dot{Q}_{\mathrm{c}}$ is the convective heat transfer rate from the heated wire to the prongs supporting it, $\dot{Q}_{\mathrm{r}}$ is the radiation heat transfer rate, and $\dot{Q}_{\mathrm{s}}$ is the heat storage rate. This assumes that the forced convection rate is much greater than the natural convection rate. For hot-film probes, which have a thin layer of conductive material on a substrate, an additional term must be added for the heat loss to the substrate as this greatly affects its frequency response. The convective loss to the supporting prongs can represent a substantial proportion (~15%) of the total heat loss. For a finite length wire, the preceding relationship can be expressed in terms of the fluid velocity as

$$\frac{I^2 R_{\mathrm{w}}}{R_{\mathrm{w}} - R_{\mathrm{a}}} = A + BU^n$$

where I is the current through the wire, R_{w} is the resistance of the wire at its operating temperature T_{w}, R_{a} is the resistance of the wire at the temperature of the fluid T_{a}, U is the velocity of the fluid, and A, B, and n are constants. A and B depend on the temperature coefficient of the wire; the density, the viscosity, and the specific heat of the fluid; and the diameter and the length of the wire. A, B, and n must be determined through calibration of a specific probe design. The voltage across the hot-wire element is

$$\frac{E_{\mathrm{w}}^2}{R_{\mathrm{w}}} = (A + BU^n)\alpha_0 R_0 (T_{\mathrm{w}} - T_{\mathrm{d}}) \tag{7}$$

where α_0 is the average temperature coefficient of the wire and R_0 is its resistance at 0°C.

In the constant temperature mode, the probe is connected in a feedback circuit to maintain a constant temperature difference ($T_{\mathrm{w}} - T_{\mathrm{a}}$) as shown in Fig. 6. The voltage across the probe, E, is then used as a measure of the fluid velocity. From Eq. (7), it can be seen that the voltage across the wire, and hence across the probe, depends on both the velocity of the fluid and the temperature difference. However, the sensitivity to changes in velocity is greater than the sensitivity to small changes in the ambient temperature (12). Furthermore, the sensitivity to velocity increases with temperature difference and the sensitivity to ambient temperature decreases. Therefore, constant temperature, hot-wire anemometers (HWA) are operated at the largest temperature difference that the wire can sustain. The exponential nature of the voltage-velocity relationship, while being highly nonlinear, means that the relative sensitivity stays approximately constant over a wide measurement range. Hence, HWA systems can be designed to operate at low air velocities as well as supersonic air velocities. The sensitivity will change in the presence of dust, smoke, oil vapor, and other contaminants.

PRACTICAL CONSIDERATIONS

Within the limitations of the transducer, direct measurement of a variable is preferable to indirect measurement. However, the measurement situation may impose constraints that require such indirect measurements. For example, a low-frequency velocity signal may result in unacceptable signal resolution for a direct velocity transducer, and a displacement transducer followed by differentiation may be preferred. However, high-frequency noise introduced on the displacement signal may result in high apparent velocities after differentiation. Care must be taken in filtering the displacement signal to reduce the noise bandwidth without removing signal information. Similarly, at high frequencies, accelerometers may be the transducers of choice followed by integration. Here offset errors can result in a drift in the calculated velocity. Digitization of the signal prior to integration will remove the drift associated with analog integrators. However, offset voltages can occur in the analog amplification of the signal and in the analog to digital conversion. The mechanical resonance of the transducer and the apparatus on which it is mounted must also be known in order to avoid errors whenever step or impulse forces are present or when measuring high-frequency velocities such as occur in vibration.

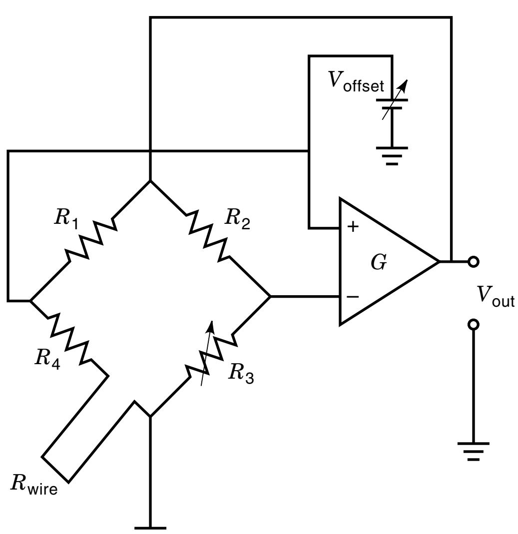

Figure 6. Constant temperature circuit for a hot-wire anemometer. R_3 may be a sensing element for ambient temperature rather than for balancing the bridge. The differential amplifier has gain G.

As in any measurement situation, loading effects must also be taken into consideration. Mechanical loading occurs when the transducer adds inertia to the system, through frictional losses, or when aerodynamic drag is increased. In flow measurement, the transduction process may introduce a pressure drop similar to a voltage drop when measuring electric current. This pressure drop must be kept sufficiently small such that the reduction in velocity is within an acceptable error limit for the measurement. Flow disturbances upstream of the transducer can cause measurement errors, but the transducer may also introduce flow disturbances that affect the process under measurement. This is particularly true when the velocity profile in a boundary layer is being investigated. Particles present in the fluid may cause abrasion of the transducer, or the transducer may cause accumulation of the particles, which then results in an excess pressure loss.

LINEAR ELECTROMAGNETIC INDUCTION VELOCIMETERS

Electromagnetic transducers (and sensors based on variable inductance and variable reluctance) tend to be mechanically robust and relatively immune to contamination from humidity, dirt, and grease. This type of transducer generates electrical energy from the motion of the system under measurement. Therefore, mechanical loading effects and energy available must be taken into consideration when choosing a suitable transducer.

The coil and magnetic field can be arranged such that linear motion of the coil with respect to the field induces a voltage across the coil. One way of doing this is to have the coil in motion, as illustrated in Fig. 1(a). As long as the coil is not completely over the magnet, the number of flux linkages will change with position, and hence a voltage will be generated. Since the mass of the coil is usually less than the mass of the magnet, this arrangement has a higher mechanical resonant frequency than a moving core transducer. A moving core transducer is typically arranged as shown in Fig. 1(b), with two coils wound and connected in series opposing fashion. In this case, the coil is substantially longer than the magnet. As the flux linkages increase in one coil, they will decrease in the other, but with the series opposing connection, the sensitivity will be doubled.

Two sources of error affect the output of an electromagnetic velocimeter (13). The linear range (or stroke length) of the transducer is that distance where the core is fully within the two coils. As the core moves through the coils at a constant velocity, some variation in the output amplitude will occur. This is referred to as the linearity error. However, the transfer function of the transducer—that is, output voltage versus velocity input—will also have some nonlinearity—the characteristic linearity error. Decalibration can occur due to exposure to high temperature or mechanical shock as these affect the magnetization of the permanent magnet core. The stroke length may be 10 mm to 600 mm, and the sensitivity can be as high as 20 $mV \cdot mm^{-1} \cdot s$ (14).

A specialized version of this type of velocimeter is the seismic vibration transducer (15). In this device, the coils are attached directly to the case of the transducer, and the permanent magnet core is suspended within the coils by two springs. The core and springs form a second-order system with a high-pass frequency response. The components are chosen to provide a low resonant frequency (<1 Hz) with a critically damped or slightly underdamped frequency response. Above resonance, the core will stay fixed in space with the case (and coils) moving with the vibrating structure to which it is attached. The magnitude of the induced voltage will be constant with respect to vibration frequency for frequencies above approximately three times the resonant frequency of the system. The voltage magnitude will be directly proportional to the velocity of the case. The electrical load impedance of any circuitry connected to the coil must be at least 10 times the coil resistance. A load impedance less than this will affect both the frequency response and the sensitivity of the transducer. The practical upper frequency limit for such devices is approximately 2 kHz (16).

ELECTROMAGNETIC FLOW METERS

As mentioned previously, electromagnetic flow meters are effectively Hall effect devices. In this case, the electric current is in the form of ions in a liquid. Both insertion-type and in-line type meters are commercially available; these are often referred to as magnetic flow meters in commercial literature. For an in-line device, the flow meter is a section of plastic or ceramic-lined pipe that is installed in the fluid path. Two electrodes of an inert metal (e.g., stainless steel or platinum) are mounted diametrically opposite each other and flush to the inner surface of the plastic liner. Outside the plastic liner, coils are formed to create as uniform a magnetic field as possible mutually orthogonal to the flow direction and the electrodes. If the internal diameter of the flow meter is matched to the inlet and outlet pipe, then the pressure drop across the meter will only be that of a similar length of straight pipe. The coils may be excited with a dc current, a sinusoidal current, or a square-wave ac current. A dc magnetic field has the advantage of not inducing a voltage directly in the lead wires of the electrodes. However, polarization of the electrodes occurs due to creation of a space charge layer as positive ions tend to build up along one wall and negative ions along the other.

An alternating magnetic field can be used to reduce this polarization. A sinusoidal magnetic field is easy to generate, and a continuous reading of voltage and hence flow can be made by rectifying and filtering the resulting signal. However, it is difficult to minimize the voltage that will be directly induced in the lead wires by the electromagnet, since the lead wires and solution will form a single-loop coil. This induced voltage artifact is at 90 electrically to the flow-induced voltage. Thus, a phase-sensitive detector can be used to attenuate the interference signal. The alternating field has the advantage of eliminating the reduced signal amplitude due to polarization. An additional error is introduced if a resistive coating builds up on the electrode surface. This creates a phase shift in the flow-induced signal. The phase-sensitive detector may then reject the flow signal if the phase shift is too large.

Square-wave, ac excitation (sometimes referred to as dc pulsed excitation) can also be used to overcome the polarization error that arises in a steady dc magnetic field. In this case, a large transient voltage will be induced when the magnetic field changes polarity, but once the transient decays, a voltage proportional to the flow will remain. This signal can then be sampled and rectified to determine the flow velocity. Since phase-sensitive detection is not required, nonconductive coating of the electrodes does not introduce an error. Gating of the signal is required to avoid saturating the input amplifier with the transient voltage. The measured signal will be equivalent to that for a dc type, but the alternating polarity substantially reduces the polarization effect.

Electromagnetic flow meters measure the average velocity of the fluid. Therefore, they must be placed in the stream at a point where the flow profile is fully developed. A rule of thumb is that there should be 10 pipe diameters of straight pipe upstream of the flow meter and 5 pipe diameters of straight pipe downstream of the flow meter. The pipe must be full of the fluid being measured. The fluid conductivity must be greater than approximately 0.5 μS/mm. The dynamic range (or turndown ratio) is typically 100 : 1 but may be as high as 3000 : 1 (17). Insertion-type flow meters are capable of accuracy of ±2%, and in-line-type flow meters are capable of ±1%.

TACHOMETERS

Tachometers are rotary or angular velocity transducers. Although angular velocity may be of interest itself, tachometers also find use in measuring linear velocity. Long stroke length (>0.25 m) velocity transducers are usually impractical or uneconomic, but a wheel or gear can usually be set up to convert the linear motion to rotary motion.

Generating tachometers are based on the same principles as electric power generators, and as such can be either ac or dc generators. A dc tachometer comprises a permanent magnet to establish a constant magnet flux through a rotor that has multiple coils each separately connected to a commutator. The advantage of a dc tachometer is that its output is rectified by the commutation of the rotor windings. The polarity of the output voltage depends on the direction of rotation. The output is linear with respect to angular velocity, although there will be some ripple (6% to 8%) (18) in the signal due to the commutation process. The ripple frequency is directly proportional to the angular velocity and the number of poles on the commutator. The brushes require some maintenance and eventual replacement over time. The sensitivity of dc tachometers is typically 2.5 to 10 V/1000 rev/min (19).

Generating ac tachometers, on the other hand, do not require commutators and brushes, as the permanent magnet is the rotor and the voltage is taken from the stator winding.

This output is sinusoidal with a frequency proportional to the angular velocity of the rotor. The amplitude of the generated voltage is also proportional to the angular velocity; however, the direction of rotation cannot be determined from the output signal. By using the frequency of the output rather than the amplitude, errors due to temperature variation and loading effects can be minimized. Squaring of the output also lends itself to digital processing of the signal.

More commonly, ac tachometers are not of the generating type, but they are based on variable mutual induction between two stator windings. The rotor may be a squirrel cage, and the two windings are at 90° to each other. One winding is excited sinusoidally at frequency ω_s. Then the output will be of the form

$$e = k\omega_s\omega_r \sin \omega_s t$$

where ω_r is the angular speed of the rotor. Although the mains distribution frequency is often used for the excitation field, in electrically noisy environments an alternative frequency can be chosen so that a tuned filter can be used to eliminate mains interference. Ac tachometers typically have sensitivities similar to those of dc tachometers. Compensating thermistors with a negative temperature coefficient may be used to reduce temperature effects on winding resistance.

Digital tachometers use proximity detectors that give a pulse output as a sensed object passes the transducer. Tachometers with a pulse output may use any of the following: electromagnetic transduction, Hall effect, eddy current, variable reluctance, optical reflectance, or shaft encoder. An electromagnetic induction tachometer has a coil wound around a permanent magnet placed next to a toothed ferromagnetic rotor (i.e., a steel gear or fan) or key way in a rotor. The reluctance of the magnetic path will be different for a gear tooth passing close to the coil compared to when a gap in the gear is near the coil. This change in reluctance will create a change in magnetic flux and hence will generate a voltage pulse across the coil. A variable reluctance proximity detector is similar in physical layout; however, the coil is energized with a constant current. The voltage across the coil changes as the reluctance of the magnetic path changes. A Hall effect transducer can be placed between a stationary permanent magnet and the rotating gear teeth. Again, the change in reluctance will cause a voltage pulse to occur. However, in this case, the magnitude of the pulse will not be affected by the angular velocity as occurs for the electromagnetic induction and variable reluctance types. Eddy current proximity transducers can also be used. In this case, a coil in close proximity to an electrically conducting rotor such as a gear or fan is excited at radio frequency (RF) frequencies. The resulting ac magnetic field will create eddy currents in the rotor teeth (or blades) when they pass close to the coil. The induced currents change the self-inductance of the coil and, therefore, will change the voltage across the coil. Reflective digital tachometers usually require a special reflective target be mounted on the rotating component. A light emitting diode (LED) or other light source is aimed at the target, and a photodetector emits a pulse each time the target rotates into its field of view. Angular velocities up to 1,000,000 rpm can be measured with this type of tachometer (20). Optical shaft encoders are also used in pulse-type tachometers. Here a LED/phototransistor pair is aligned with a rotating mask revolving between them. The mask has alternately opaque and transparent sections evenly spaced around its perimeter. Except for the shaft encoder, the digital tachometers do not require mechanical contact with the rotating component and have a minimal mechanical loading effect.

Two signal processing schemes can be used with pulse-type tachometers once the output has been squared. As a direct replacement for analog output tachometers, the output can be fed to a frequency to voltage converter (5). In this case, the pulses must be of constant duration independent of the rotational velocity. A completely digital technique can also be employed. The velocity is determined by counting the output pulses over a fixed duration of time. Very low angular velocities can be measured with better resolution by counting the number of "clock ticks" of a high-frequency clock that occur between successive pulses of the tachometer output.

VELOCITY MEASUREMENT USING ULTRASOUND

Flow Meters

Industrial ultrasonic flow meters may use either the Doppler shift technique or the time of flight. The former has the potential to provide information about the velocity profile across the flow pattern; the latter has the advantage of being usable in "clean" liquids and gases. Doppler shift techniques require reflective targets. Frequently, the targets are bubbles or particles that are either inherently present or are introduced into the fluid. It is also possible to use turbulent swirls within the fluid as the reflectors (21,22). Because of the need for reflective targets, Doppler techniques are not usable in gases.

Ultrasonic flow-meter transducers are mounted in one of three ways: clamped on the outside of the pipe, inserted through an opening in the side of the pipe, or installed in-line via a spool piece. Clamp-on transducers can be mounted on most existing pipe—steel, iron, hard PVC, or glass. Some transducers may also work with concrete lined pipes (23). The alignment of clamp-on transducers must take into account the diffraction of the wave at the two wall-fluid interfaces. The signal will also be substantially reduced in amplitude because of the reflections that occur at these interfaces due to the large acoustic impedance mismatch between the pipe wall and the fluid. For this reason, clamp-on transducers are most frequently used with liquids rather than gases. Clamp-on transducers may be used where the fluid is corrosive, abrasive, or at high temperature, since the transducer does not come into direct contact with the fluid.

The measurement of flow velocity requires that a laminar flow profile be developed upstream of the flow transducer. This may require as much as 10 pipe diameters of pipe upstream of the transducer and 5 pipe diameters of pipe downstream of the transducer. [However, where vortices are the reflective targets, the flow meter must be located 1 to 3 pipe diameters below a 90° elbow (21).] Doppler ultrasound flow transducers require particles (or vortices) to be present. These may be present by the nature of the fluid, or they may be seeded into the flow. The size and concentration of the particles required will depend on the frequency of the ultrasonic signal. For example, particles must be at least 25 μL/L and 30 μm for 1 MHz ultrasound. Lower frequencies require higher concentrations and larger particles. However, high concentrations of particles can result in reduced signal to noise ratio due to excessive scattering of the signal.

Water in rivers, lakes, and ocean has enough naturally occurring particles to allow Doppler velocity measurements. Several approaches have been developed to measure water currents. Small sample volumes can be used to measure boundary layer velocities, or multiple transmitter/receivers can be used to monitor the current at several depths simultaneously. A third technique is to use range gating of the returned signal from a single transducer to scan the depth of the channel being measured. In this case, a pulse of ultrasonic energy is emitted, and the return signal is monitored for only a short time. The time between pulse emission and gating of the return signal is varied to sample at different depths. The transmitted frequency may be as low as 300 kHz for depths of 100 m or more. Range gating has also been applied to medical ultrasound systems and for flow in pipes and tanks (24).

Flow meters and anemometers based on acoustic or ultrasonic transit time techniques are finding increased use industrially (25). One example is a wind speed system that uses three pairs of transmitter/receivers that are oriented 120° with respect to each other (26). This combination allows the velocity—that is, both magnitude and direction—to be calculated, assuming that the flow is in the plane of the transceiver pairs. Ultrasonic anemometers can measure down to zero velocity, whereas cup anemometers have a threshold speed of about $2\ \text{km} \cdot \text{h}^{-1}$. Where improved accuracy is needed, such as in custody transfer of natural gas, several transmitter/receiver pairs may be used across different chords of the pipe to improve the estimate of the average flow velocity. Four beam paths may be sufficient if the flow profile is not turbulent, or two crossed sets of four paths may be used where some turbulence occurs (27).

Medical Ultrasound Systems

Ultrasound is used extensively in medicine, not only for flow measurement but also flow visualization and imaging more generally. The reader is referred to Jensen (1) for a more complete mathematical development of the techniques described here. A shorter explanation is also available in an article by Routh (28). Medical ultrasound systems use transmitted frequencies in the range of 2 MHz to 10 MHz. Higher frequencies give better spatial resolution but have less penetration due to increased attenuation. In velocity measurement, the most common application is blood flow, but moving structures such as heart valves are also of clinical interest. Flow velocity varies from $0.01\ \text{m} \cdot \text{s}^{-1}$ to $10\ \text{m} \cdot \text{s}^{-1}$. Amplifiers for the returned ultrasonic signal have a gain function that increases with time after pulse emission. This compensates for the attenuation that occurs as the signal passes through more tissue.

The ultrasound signal is emitted by a one-dimensional array of elements whose drive signals are controlled electronically to steer and focus the signal at the desired position in the tissue or blood vessel. These transducer arrays are either linear or convex. The size and shape of the array depends on the intended site of use: transcutaneous, transesophageal, transvaginal, or transrectal. With the speed of sound in tissue (approximately $1540\ \text{m} \cdot \text{s}^{-1}$), 3500 traces can be scanned each second at a penetration depth of 200 mm. Most ultrasound systems use pulsed rather than continuous wave signals. Pulsed wave systems have the advantage of allowing a two-dimensional image to be obtained with the velocity image overlain on it. The operator can then indicate, by means of a cursor on the display, the approximate direction of flow so that the actual velocity can be calculated. The display may be color enhanced with flow toward the transducer being red and flow away from the transducer blue. Pulsed wave signals are usually referred to as pulsed Doppler; however, Jensen (1) provides a strong mathematical derivation to show that the velocity information is actually contained in the time shift of successive pulses rather than the Doppler frequency shift. The classical approach to signal processing has been to use coherent demodulation of the returned echo with the transmitter oscillator followed by low-pass filtering. The mean frequency of the demodulated signal is determined by autocorrelation. An alternate approach is to sample directly the return signal and to crosscorrelate successive pulses. This method has become feasible with development of analog to digital converters capable of sampling at the frequencies used for ultrasound imaging.

A more recent development in medical flow imaging is power or energy flow imaging, sometimes referred to as power Doppler imaging. In this case, an estimate is made of the power in the return signal. The power is not dependent on the angle of incidence of the ultrasound beam and the moving target. However, the result is only an image of where flow is occurring without any ability to estimate the velocity of the flow. Clinically, the advantage to power imaging is that smaller arteries can be resolved. This allows a better understanding of tissue perfusion. Another improvement currently undergoing investigation is three-dimensional ultrasonic velocimetry [for example, see (29)]. Two approaches for this have been identified: to use multiple receivers whose beam axes are not co-planar and to use crosscorrelation of two successive images (similar to particle image velocimetry below).

MICROWAVE VELOCIMETRY

Perhaps the most notorious velocimeter is the microwave Doppler velocimeter or radar gun—used primarily for traffic speed enforcement. The target must be electrically conductive to behave as a reflector. A continuous wave microwave signal, at about 10 GHz, is generated by a Gunn diode and varactor in a resonant cavity and is emitted from a horn antenna. The return signal is received by the same antenna, where it is led by means of a waveguide to a Schottky mixer diode, where it is mixed with a portion of the oscillator output (30). The output of the mixer is the low-frequency, Doppler shift signal. The frequency, and hence the velocity of the target, can be obtained from this signal, for example, by using a zero crossing detector (31). More complex Doppler radar systems are used in aircraft navigation systems to determine aircraft velocity (32). These are particularly useful in helicopter navigation and control because the helicopter may have long periods of low velocity when hovering. During these periods, drift in an inertial guidance system based on gyroscopes may affect the accuracy of position calculations.

The global positioning satellite (GPS) system and its Russian counterpart (GLONASS) are being used increasingly for navigation purposes. Collectively these are referred to as the global navigation satellite system (GNSS). The standard civilian GPS coded information channel (C/A on the L1 carrier frequency) has a resolution of less than 100 m 95% of the time (33). For short time intervals, this level of repeatability leads to highly erroneous velocity estimates based on successive positions and the elapsed time. However, it is possible to use the carrier signal rather than the coded information to improve both position and velocity calculations. Carrier phase tracking (33,34) takes advantage of the 1000-fold improvement in spatial resolution by using the wavelength of the carrier (approximately 190 mm) to obtain position information. Surveying instruments are available (34,35) that provide 10 mm resolution. They do not suffer from the dithering of the coded information channel referred to as selective availability. The most recent instruments do not require a base station at a known location to provide this level of accuracy. Thus, successive estimates of position can provide velocity information. Since GNS receivers must have highly stable clocks, time information is inherently readily available.

A third use of electromagnetic waves in velocimetry is measuring high-latitude ionospheric convection, which are currents of ionized particles that flow due to the interaction of the solar wind with the earth's magnetic field (36). The velocity of the ionized particles flowing in these field aligned currents can be measured using the Doppler shift that arises when an electromagnetic beam is reflected off the particles. The radar frequencies are in the range of 8 MHz to 20 MHz with corresponding wavelengths of approximately 10 m. Therefore, the reflective target cannot be individual charged particles, but irregularities in the electron density that have a size of approximately one-half of the wavelength. Particle drift velocity is on the order of 300 $m \cdot s^{-1}$ to 400 $m \cdot s^{-1}$ and may exceed 1000 $m \cdot s^{-1}$. With two radars separated by several thousand kilometers, it is possible to calculate the magnitude and direction of the currents in the plane of the radar beam.

OPTICAL VELOCIMETRY

Particle Image Velocimetry

Particle image velocimetry (PIV) is used for imaging complex flow profiles (8). Because of the cost and complexity of the apparatus, this technique is used primarily in research applications. Areas of application include combustion flows, unsteady aerodynamic flow around rotors, turbulent water flow, flows in internal combustion engines, and natural convection.

A laser beam is passed through a cylindrical lens to create a sheet of light that illuminates the fluid field. The thickness of the laser sheet can be controlled by interposing a spherical lens after the cylindrical lens. The flow must be in the plane of the illuminating sheet, and the fluid must be transparent to the wavelength of the illuminating source. The fluid must have naturally occurring particles, or it must be seeded with particles appropriate to the fluid and the desired frequency response. Particles can range from 0.2 μm to 40 μm, depending on the particle dynamics of the flow. Particular care must be taken in determining the particle size required to image swirling flows. Light from the particles is imaged onto a camera, and two successive images are taken. If irregularities in the flow pattern are smaller than the area being imaged, then subsequent processing is done on overlapping subsets of the total image. The light source is usually a pulsed laser with short duration (10 ns) pulses. In a dual laser system, the time between pulses may be adjusted from 200 ns to 0.5 s (37). The time between pulses must be known, of course, for the speed to be calculated. If both pulses are captured on the same image, then there will be an ambiguity as to the direction of flow. The image may be captured on a photographic transparency or a CCD video camera. The former has the advantage of high resolution; the latter has the advantage of representing the image electronically so that it can be readily converted into a digital representation.

The displacement information contained in the double exposure image can be extracted in a number of ways. If the image is on a transparency, this can be illuminated by a laser beam. The particle image pairs will cause Young's fringes to be formed from which the image displacement can be inferred. A transparency can be made of the Young's fringes. When this is, in turn, illuminated by a laser source, the autocorrelation function is created. The two first-order side peaks represent the displacement distance between the two images. Alternatively, the Young's fringes can be digitized via a CCD camera, and a digital autocorrelation can be calculated. If a CCD camera is to be used, then the original two PIV images can be captured directly on a single frame, and digital autocorrelation can be performed. If the velocity is sufficiently slow, successive images may be on the even and odd fields of a frame. However, this reduces the spatial resolution. Where separate images have been obtained, crosscorrelation or maximum quadrature difference can be used to determine the displacement (38).

A variety of techniques has been used to separate the two images to avoid the directional ambiguity. A rotating mirror can be used before the camera to move the second image by more than the largest expected displacement. This value can then be subtracted from that calculated by one of the aforementioned methods. This is particularly useful where turbulence prevents a priori knowledge of the direction of flow. In a dual laser system, the two beams can be given different optical polarization, and a birefringent crystal, such as calcite, can be used to shift one beam. Wirth and Baritaud (9) describe a method of using a ferroelectric liquid crystal retarder on the imaging path (rather than the illuminating path). Their technique resulted in one image with only the first laser pulse and a second image with the usual double image. A CCD camera that has storage cells associated with each pixel element of the camera is capable of acquiring two full frames of information at short time intervals (39). In this case, the image information is transferred in parallel from the light-sensitive elements to the storage cells prior to the second laser pulse. This technology has allowed on-line calculation of velocity vectors for flow velocities up to supersonic speeds. Such high-speed image calculations are usually performed by dedicated computers configured to maximize the throughput of parallel calculations. Grant (8) provides a review of developments in the field, which are under development at the time of this writing.

Laser Doppler Anemometry

Laser Doppler anemometry (LDA) is also known as laser Doppler velocimetry, laser anemometry, or optical anemometry because its main application is in complex aerodynamic flow fields. The reader is referred to Durst, Melling, and Whitelaw (40) for a more complete explanation of the physics of laser Doppler anemometry. As with particle image velocimetry, no flow disturbance occurs; particles must be present; and there must be optical access to the flow. The Doppler frequency shift is detected as a phase shift by creating an interference pattern between the Doppler-shifted beam and a reference beam. The interference fringes will have a beat frequency because of the Doppler shift. The beat frequency is proportional to the flow velocity perpendicular to the source of illumination, unlike Doppler ultrasound, which measures the component parallel to the insonation beam. The beat frequency can then be detected with a photomultiplier tube or other photodetector. The technique has the advantages of high accuracy, wide dynamic range (a few microns per second to Mach 8) (37), and fast response time.

Three modes of operation are possible: dual beam (or fringe or differential Doppler), reference beam, and two scattered beam. The dual beam technique uses a beam splitter to create two beams from a single laser. By means of appropriate optical elements, including optical fibers, the two beams are focused on the same volume region of the flow but from different angles. A light-collecting lens and mask are used to image the interference fringes from a single particle onto a photodetector. The optical axis of the collecting side is symmetrical with respect to the two illuminating beams. This approach has a large solid angle but requires relatively few particles in the flow. The reference beam technique has a smaller solid angle and can be used in particle-rich flows. Both the reference beam and the scattering beam illuminate the flow region, as before. However, in this case, the optical axis of the collecting system is coincident with the axis of the reference beam. The two-scattered-beam configuration has a single beam illuminating the flow volume, but there are two collecting axes. The scattered light along these axes is then combined to create the desired interference fringes. The collected light can be backscattered rather than forward scattered, which means that optical access is required from only one side of the flow field. This last approach has the further advantage of being readily adapted to measure two- or three-dimensional flow components by having two or three mutually orthogonal collecting systems.

As with other Doppler shift techniques, LDA will have directional ambiguity. Where this is problematic, such as with turbulent flow, a rotating diffraction grating on one of the two illuminating beams can be used to create a frequency preshift. Alternately, the two beams can have their wavelengths shifted in opposite direction by being passed through a Bragg cell (41).

This technique has also been applied to the study of perfusion of soft tissues in medicine (42). In this application, a laser beam is scanned across the surface of the tissue by means of a rotating mirror. The reflected light is then processed in a manner similar to the aforementioned techniques. This is one of the few methods that can image the low blood flow in peripheral vasculature. However, only relative flow measurements can be made, not absolute measurements.

Time-of-Flight Optical Velocimeters

If the radar gun is the most notorious velocimeter, then the lidar (or ladar) is quickly gaining a similar status for the same reason. This is the optical replacement for the radar gun in traffic speed enforcement. Lidar (light or laser distance and ranging) is based on the time of flight of a short pulse of laser light emitted and received by a single unit. Since the speed of light is constant with respect to temperature and atmospheric conditions, the time taken will be directly proportional to the distance. In fact, commercial units (43,44) include the ability to measure range as well as speed. Successive measurements can then be used to calculate the speed of the target. Because of the short duration of the laser pulses, up to 60 pulses may be used in a single speed measurement, which takes 0.3 s to perform. The infrared laser diodes have a beam divergence of 3 mrad (that is, 3 m in 1000 m) so individual vehicles can be targeted as reflectors. A geometric correction must be made if the target is not moving in line with the laser beam path.

Optical Gyroscopes

Gyroscopes measure rotational velocity usually for navigation purposes or stabilization of a platform. The propagation velocity of electromagnetic waves is not affected by motion of the medium through which they are passing, as was the case for acoustic waves. That is, electromagnetic waves, and photons particularly, can be thought of as moving in an inertial frame of reference. However, suppose that three mirrors are mounted on a platform that may be rotated as shown in Fig. 7. A photon traversing the path in the clockwise direction will experience a longer path length than one traversing in the opposite direction if the whole apparatus rotates clockwise. This is known as the Sagnac effect (45). Two types of optical gyroscopes have been developed based on the Sagnac effect: ring laser gyroscopes and fiber optic gyroscopes.

In a ring laser, the rotating ring is filled with the lasing medium. The output is two independent beams—one in each

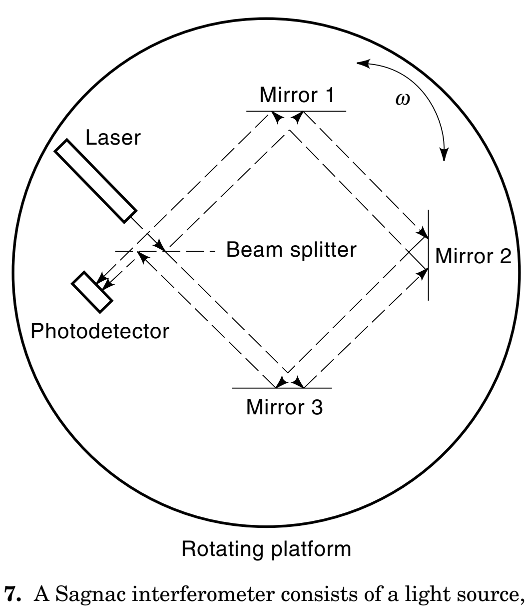

Figure 7. A Sagnac interferometer consists of a light source, a closed optical path, and a means of detecting the fringes that are generated as the platform rotates.

direction. The two beams will be at different frequencies (that is, wavelengths) since there must be an integer number of wavelengths in the resonant path (46). The two path lengths will be different by the amount

$$\Delta p = \frac{2\Omega A}{c}$$

where p is the path length, Δp is the difference in path length, Ω is the rotational velocity, A is the projected area of the ring, and c is the speed of light. This leads to a difference in time it takes for light to travel around the ring:

$$\Delta t = \frac{2\Delta p}{c}$$

The wavelength shift can be measured through interference fringes created by mixing the two output beams. Ring lasers are used in research applications such as measuring the rotation of the earth.

Fiber optic gyroscopes (FOG) have counterpropagating light that is injected into opposite ends of a coil of single-mode optical fiber. The light source may be a laser or a superluminescent light emitting diode. The latter has the advantage of reducing one source of phase error—namely, the Kerr effect (47). If the optical fiber undergoes rotation in the plane of the coil, then the two beams will have had a different time of flight, as mentioned previously. This leads to a phase shift that can be detected through interference fringes. Multiple turns of the coil increase the phase shift and hence the sensitivity of the gyroscope:

$$\Delta\phi = \frac{8\pi\Omega NA}{\lambda c}$$

where $\Delta\phi$ is the phase shift, Ω is the angular velocity, N is the number of turns, A is the area, λ is the wavelength, and c is the speed of light. Note that in both the FOG and the ring laser, it is the area of the closed path that is important, not the path length. A detector placed at the output of the interfering beams has an amplitude that is dependent on the phase shift (48):

$$P_{\mathrm{D}} = \frac{P_{\mathrm{in}}(1 + \cos\Delta\phi)}{2\,\mathrm{Loss}}$$

The maximum sensitivity will occur when the beams are 90° optically with respect to each other. A phase modulator is, therefore, usually placed in the path of one of the incoming beams. The phase modulator has the additional advantage of causing the interferometer to oscillate ±90°. Thus, the otherwise dc signal becomes an ac signal at the frequency of the phase modulator. A tuned filter is then used on the output of the detector to reduce $1/f$ noise.

FOGs are manufactured to cover a wide range of performance requirements. Inertial navigation quality FOGs have maximum sensing rates of up to 400° per second and stability of 0.0001° per hour. At the low end of the performance scale, the maximum rate is 100° per second and the bias stability is 100° per hour. A typical FOG might have 1000 m of optical fiber on an 84 mm diameter spool (49).

Hot-Wire Anemometry

Hot-wire anemometry (HWA) is based on the physical principle that heat dissipation from a heated object is dependent on the mass flow of the medium in which the object is immersed. The heat dissipation is dependent not only on velocity but also on temperature, pressure, specific heat, and density of the medium. In most cases, HWA is used for air velocity measurements, in which case the relative humidity of the air affects its density and specific heat. For environmental air speed monitoring, such as in building ventilation systems, the atmospheric pressure and relative humidity must be known, or assumed, to calculate velocity from the mass flow rate. Since the technique is based on a differential temperature measurement, many instruments built for environmental monitoring also include the capability of measuring the ambient air temperature (20). Measurement of atmospheric pressure may also be included (50). Air speed from 0 to 60 $\mathrm{m \cdot s^{-1}}$ can be measured by such instruments. In instruments designed for mass flow measurements rather than velocity measurements, multiple sensors may be included on a single mount to obtain a better estimate of the flow profile (50).

HWA is also used to measure complex flow fields involving high air speeds and/or turbulence. Although HWA inherently alters the flow field, it is often used instead of laser Doppler anemometry or particle image velocimetry because of its lower cost and no requirement for optical access to the flow field or an optically clear fluid. In turbulent flow, the frequency response is an important figure of merit as well as the maximum velocity. Because of their small size, hot-film probes can be designed with a frequency response up to 300 kHz. Cone- or wedge-shaped hot-film probes are preferred over cylindrical probes due to greater strength (50). The film material is usually platinum and the substrate material is quartz. If the probes are coated, they can be used in conductive liquids, although this will increase the response time of the probe.

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VELOCITY MEASUREMENT. See Velocimeters.

VERIFICATION, FORMAL METHODS. See Design verification and fault diagnosis in manufacturing.

VERY HIGH SPEED INTEGRATED CIRCUITS. See VLSI Circuit layout.