

Instrumentation Engineering

Giselle Dortch

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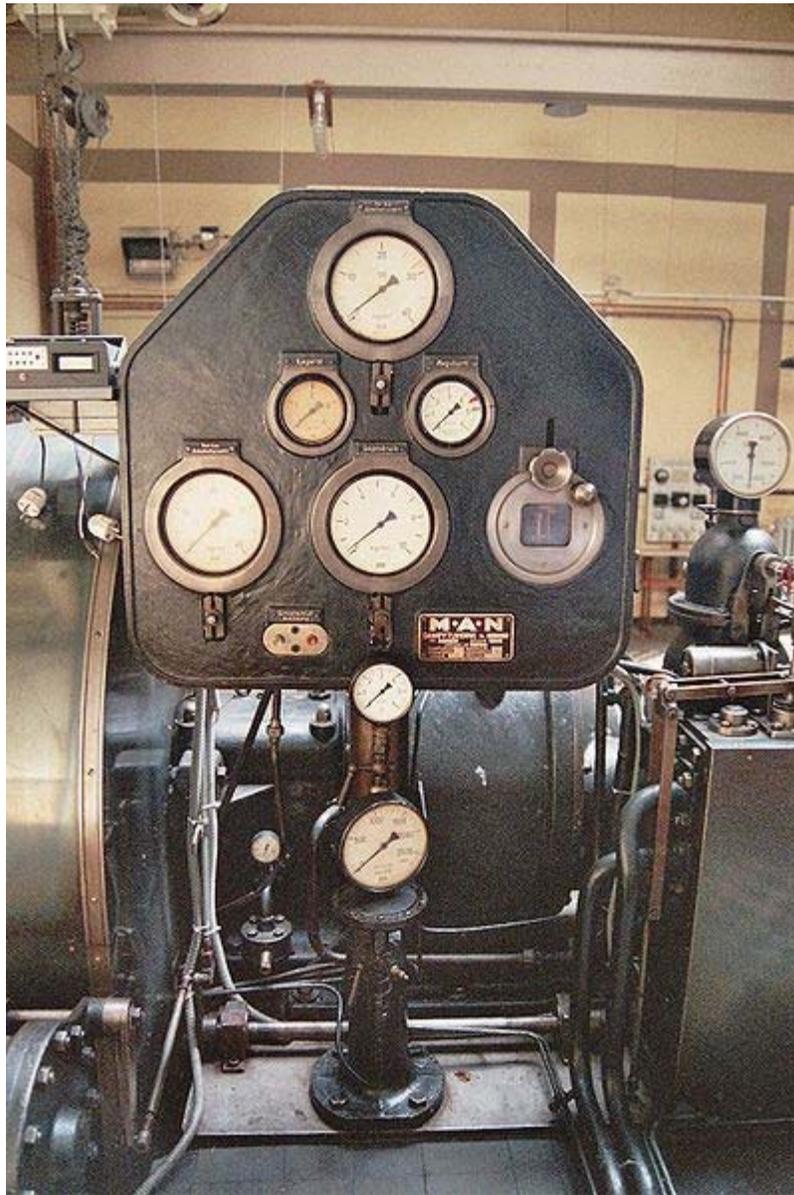
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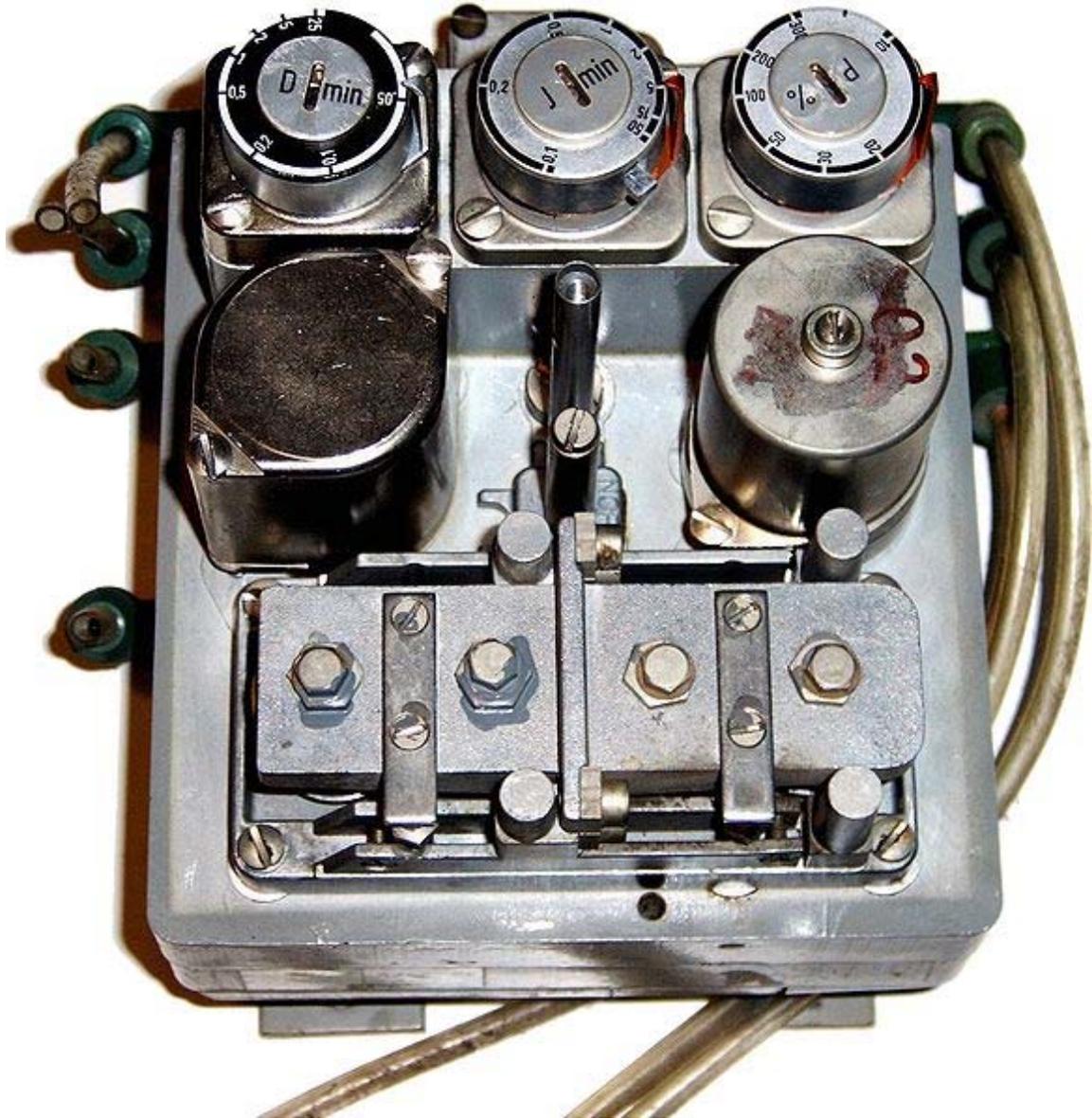
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Chapter 1

Instrumentation



A control post of a steam turbine.



Pneumatic PID controller.

Instrumentation is defined as the art and science of measurement and control.

An instrument is a device that measures and/or regulates process variables such as flow, temperature, level, or pressure. Instruments include many varied contrivances which can be as simple as valves and transmitters, and as complex as analyzers. Instruments often comprise control systems of varied processes such as refineries, factories, and vehicles. The control of processes is one of the main branches of applied instrumentation. Instrumentation can also refer to handheld devices that measure some desired variable. Diverse handheld instrumentation is common in laboratories, but can be found in the household as well. For example, a smoke detector is a common instrument found in most western homes.

Output instrumentation includes devices such as solenoids, valves, regulators, circuit breakers, and relays. These devices control a desired output variable, and provide either remote or automated control capabilities. These are often referred to as final control elements when controlled remotely or by a control system.

Transmitters are devices which produce an output signal, often in the form of a 4–20 mA electrical current signal, although many other options using voltage, frequency, pressure, or ethernet are possible. This signal can be used for informational purposes, or it can be sent to a PLC, DCS, SCADA system, or other type of computerized controller, where it can be interpreted into readable values and used to control other devices and processes in the system.

Control Instrumentation plays a significant role in both gathering information from the field and changing the field parameters, and as such are a key part of control loops.

History

In the early years of process control, process indicators and control elements such as valves were monitored by an operator that walked around the unit adjusting the valves to obtain the desired temperatures, pressures, and flows. As technology evolved pneumatic controllers were invented and mounted in the field that monitored the process and controlled the valves. This reduced the amount of time process operators were needed to monitor the process. Later years the actual controllers were moved to a central room and signals were sent into the control room to monitor the process and outputs signals were sent to the final control element such as a valve to adjust the process as needed. These controllers and indicators were mounted on a wall called a control board. The operators stood in front of this board walking back and forth monitoring the process indicators. This again reduced the number and amount of time process operators were needed to walk around the units. The basic air signal used during these years was 3-15 psig.

In the 1970s electronic instrumentation began to be manufactured by the instrument companies. Each instrument company came out with their own standard signal for their instrumentation, 10-50ma, 0.25-1.25Volts, 0-10Volts, 1-5volts, and 4-20ma, causing only confusion until the 4-20ma was universally used as a standard electronic instrument signal for transmitters and valves. The transformation of instrumentation from mechanical pneumatic transmitters, controllers, and valves to electronic instruments reduced maintenance costs as electronic instruments were more dependable than mechanical instruments. This also increased efficiency and production due to their increase in accuracy.

The next evolution of instrumentation came with the production of Distributed Control Systems (DCS). The pneumatic and electronic control rooms allowed control from a centralized room, DCS systems allowed control from more than one room or control stations. These stations could be next to each other or miles away. Now a process operator could sit in front of a screen and monitor thousands of points throughout a large unit or complex.

Measurement

Instrumentation is used to measure many parameters (physical values). These parameters include:

- Pressure, either differential or static
- Flow
- Temperature
- Levels of liquids etc.
- Density
- Viscosity
- Other mechanical properties of materials
- Properties of ionising radiation
- Frequency
- Current
- Voltage
- Inductance
- Capacitance
- Resistivity
- Chemical composition
- Chemical properties
- Properties of light
- Vibration
- Weight

Control



Control valve.

In addition to measuring field parameters, instrumentation is also responsible for providing the ability to modify some field parameters.

Instrumentation engineering

Instrumentation engineering is the engineering specialization focused on the principle and operation of measuring instruments which are used in design and configuration of automated systems in electrical, pneumatic domains etc. They typically work for industries with automated processes, such as chemical or manufacturing plants, with the

goal of improving system productivity, reliability, safety, optimization, and stability. To control the parameters in a process or in a particular system, devices such as microprocessors, microcontrollers or PLCs are used, but their ultimate aim is to control the parameters of a system.

Instrumentation technologists and mechanics

Instrumentation technologists, technicians and mechanics specialize in troubleshooting and repairing and maintenance of instruments and instrumentation systems. This trade is so intertwined with electricians, pipefitters, power engineers, and engineering companies, that one can find him/herself in extremely diverse working situations.

Chapter 2

Measuring Instrument



A Love Meter at a Framingham, Massachusetts Rest Stop.

In the physical sciences, quality assurance, and engineering, measurement is the activity of obtaining and comparing physical quantities of real-world objects and events. Established standard objects and events are used as units, and the process of measurement gives a number relating the item under study and the referenced unit of measurement.

Measuring instruments, and formal test methods which define the instrument's use, are

the means by which these relations of numbers are obtained. All measuring instruments are subject to varying degrees of instrument error and measurement uncertainty.

Scientists, engineers and other humans use a vast range of instruments to perform their measurements. These instruments may range from simple objects such as rulers and stopwatches to electron microscopes and particle accelerators. Virtual instrumentation is widely used in the development of modern measuring instruments.

Time, energy, power and action

Time



Time measurement device.

Time-points in the *past* can be measured with respect to the *present* of an observer. Time-points in the *future* can be fixed. But there seems to exist no device that can set time to a predetermined value (time machine), unlike it is possible with other physical quantities (for example: distance or volume). The time-point called *present* seems to move in one

direction only, the future. Entropy production and cause-and-effect observations of events correlate to this observation.

Energy



Changing energy carriers, linear momentum to angular momentum. No measurement primarily intended.

Example: In a plant that furnishes pumped-storage hydroelectricity, mechanical work and electrical work is done by machines like electric pumps and electrical generators. The pumped water stores mechanical work. The amount of energy put into the system equals the amount of energy which comes out of the system, less that amount of energy used to overcome friction.

Such examples suggested the derivation of some unifying concepts: Instead of discerning (transferred) forms of work or stored work, there has been introduced one single physical quantity called energy. Energy is assumed to have substance-like qualities; energy can be apportioned and transferred. Energy cannot be created from nothing, or to be annihilated to nothing, thus energy becomes a conserved quantity, when properly balanced.

Describing the transfer of energy two dictions, two ways of wording are used:

(energy carriers exchanging energy) Physical interactions occur by carriers (linear momentum, electric charge, entropy) exchanging energy. For example, a generator transfers energy from angular momentum to electric charge.

(energy forms transforming energy) Energy forms are transformed; for example mechanical energy into electrical energy by a generator.

Often the energy value results from multiplying two related quantities: (a generalized) potential (relative velocity, voltage, temperature difference) times some substance-like quantity (linear momentum, electrical charge, entropy). — Thus energy has to be measured by first choosing a carrier/form. The measurement usually happens indirectly, by obtaining two values (potential and substance-like quantity) and by multiplying their values.

Power (flux of energy)

A physical system that exchanges energy may be described by the amount of energy exchanged per time-interval, also called power or flux of energy.

Action

Action describes energy summed up over the time a process lasts (time integral over energy). Its dimension is the same as that of an angular momentum.

- A phototube provides a voltage measurement which permits the calculation of the quantized action (Planck constant) of light.

Mechanics

This includes basic quantities found in Classical- and continuum mechanics; but strives to exclude temperature-related questions or quantities.

Length (distance)

- Altimeter, height
- Architect's scale
- Caliper
- Electronic distance meter
- Engineer's scale
- Frequency comb
- Gauge blocks
- GPS, indirect by runtime measurement of electromagnetic waves in the GHz-range
- Interferometer
- Laser rangefinder, indirect by runtime
- Opisometer
- Feeler gauge, used in metal working to measure size of gaps
- Radar antenna, indirect by runtime measurement of electromagnetic waves around the microwave region (radar)
- Rule
- Surveyor's wheel
- Tachymeter
- Tape measure
- Taximeter, measure usually

measurement of coherent electromagnetic waves around the visible light region (lidar)

- Metric scale
- Micrometer
- Odometer

includes a time component as well

- Travelling microscope
- Ultrasound distance measure, indirect by runtime measurement of sound waves (sonar, Echo sounding)
- Urethra gauge, cylindrical circumferencial measurement device.

Area

- Planimeter

Volume



A measuring cup, a common instrument used to measure volume.

- buoyant weight (solids)
- overflow trough (solids)
- Measuring cup (grained solids, liquids)
- Flow measurement devices (liquids)
- Graduated cylinder (liquids)
- Pipette (liquids)
- Eudiometer, pneumatic trough (gases)

(if the mass density of a solid is known, weighing allows to calculate the volume)

Mass- or volume flow measurement

- Gas meter
- Mass flow meter
- Metering pump
- Water meter

Speed (flux of length)

- Airspeed indicator
- Radar gun, a Doppler radar device, using the Doppler effect for indirect measurement of velocity.
- Speedometer
- Tachometer (speed of rotation)
- Tachymeter
- Variometer

Acceleration

- Accelerometer

Mass



A pair of scales: An instrument for measuring mass in a force field by balancing forces.

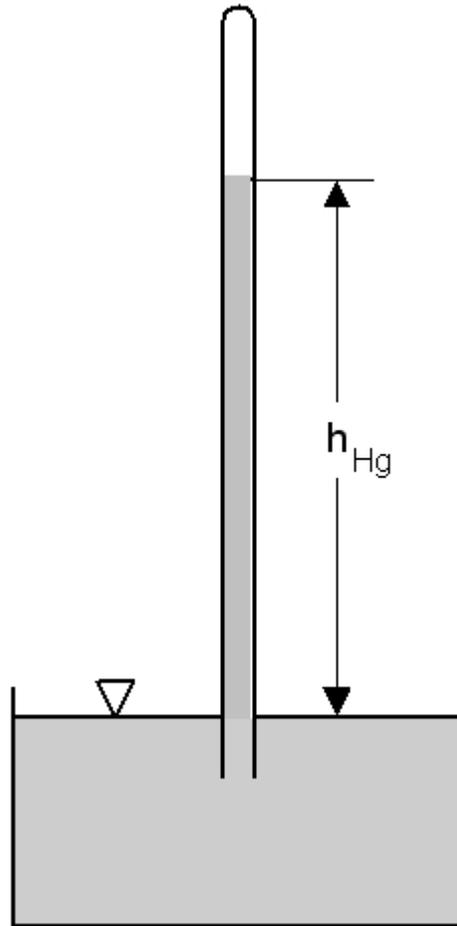
- Balance
- Automatic checkweighing machines
- Katharometer
- Weighing scales
- Inertial balance
- Mass spectrometers measure the mass-to-charge ratio, not the mass

Linear momentum

- Ballistic pendulum

Force (flux of linear momentum)

- Force gauge
- Spring scale
- Strain gauge
- Torsion balance
- Tribometer



Measuring absolute pressure in an accelerated reference frame: The principle of a mercury (Hg) barometer in the gravitational field of the earth.

Pressure (flux density of linear momentum)

- Anemometer (used to determine wind speed)
- Barometer used to measure the atmospheric pressure.
- Manometer see pressure measurement
- Pitot tube (used to determine speed)
- Tire-pressure gauge in industry and mobility

Angle

- Circumferentor
- Cross staff
- Goniometer
- Graphometer
- Protractor
- Quadrant
- Reflecting instruments
 - Octant
 - Reflecting circles
 - Sextant
- Theodolite

Angular velocity or rotations per time unit

- Stroboscope
- Tachometer

Torque

- Dynamometer
- De Prony brake
- Torque wrench

Orientation in three-dimensional space

Level

- Dumpy level
- Laser line level
- Spirit level
- Tiltmeter

Direction

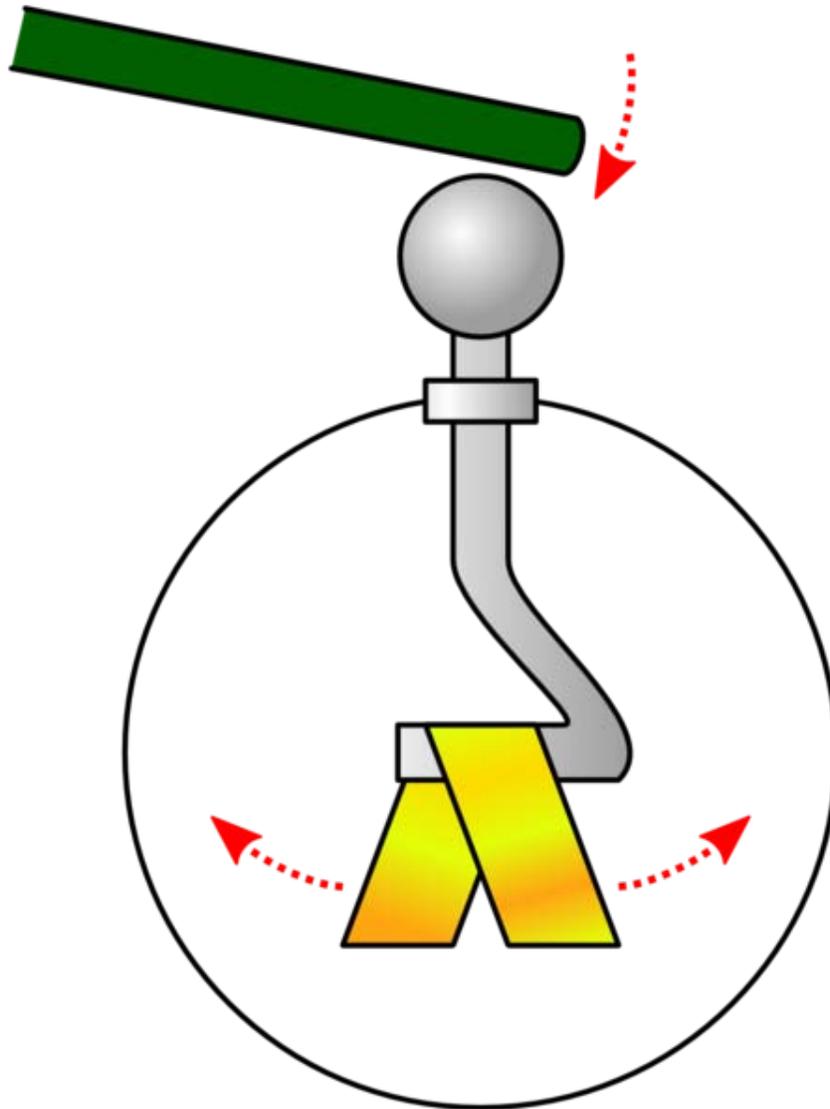
- Gyroscope

Energy carried by mechanical quantities, mechanical work

- Ballistic pendulum, indirectly by calculation and or gauging

Electricity, electronics and electrical engineering

Considerations related to electric charge dominate electricity and electronics. Electrical charges interact via a field. That field is called electric if the charge doesn't move. If the charge moves, thus realizing an electric current, especially in an electrically neutral conductor, that field is called magnetic. Electricity can be given a quality — a potential. And electricity has a substance-like property, the electric charge. Energy (or power) in elementary electrodynamics is calculated by multiplying the potential by the amount of charge (or current) found at that potential: potential times charge (or current).



An instrument for detecting net charges, the electroscope.

Electric charge

- Electrometer is often used to reconfirm the phenomenon of contact electricity leading to triboelectric sequences.
- Torsion balance used by Coulomb to establish a relation between charges and force, see above.

Electric current (current of charge)

- Ammeter
- Clamp meter
- Galvanometer

Voltage (electric potential difference)

- Oscilloscope allows to quantify time depended voltages
- Voltmeter

Electric resistance, electrical conductance (and electrical conductivity)

- Ohmmeter
- Time-domain reflectometer characterizes and locates faults in metallic cables by runtime measurements of electric signals.
- Wheatstone bridge

Electric capacitance

- Capacitance meter

Electric inductance

- Inductance meter

Energy carried by electricity or electric energy

- Electric energy meter
- Electricity meter

Power carried by electricity (current of energy)

- Wattmeter

These are instruments used for measuring electrical properties.

Electric field (negative gradient of electric potential, voltage per length)

- Field mill

Magnetic field

- Compass
- Hall effect sensor
- Magnetometer
- Proton magnetometer
- SQUID

Combination instruments

- Multimeter, combines the functions of ammeter, voltmeter and ohmmeter as a minimum.
- LCR meter, combines the functions of ohmmeter, capacitance meter and inductance meter. Also called *component bridge* due to the bridge circuit method of measurement.

Thermodynamics

Temperature-related considerations dominate thermodynamics. There are two distinct thermal properties: A thermal potential — the temperature. For example: A glowing coal has a different thermal quality than a non-glowing one.

And a substance-like property, — the entropy; for example: One glowing coal won't heat a pot of water, but a hundred will.

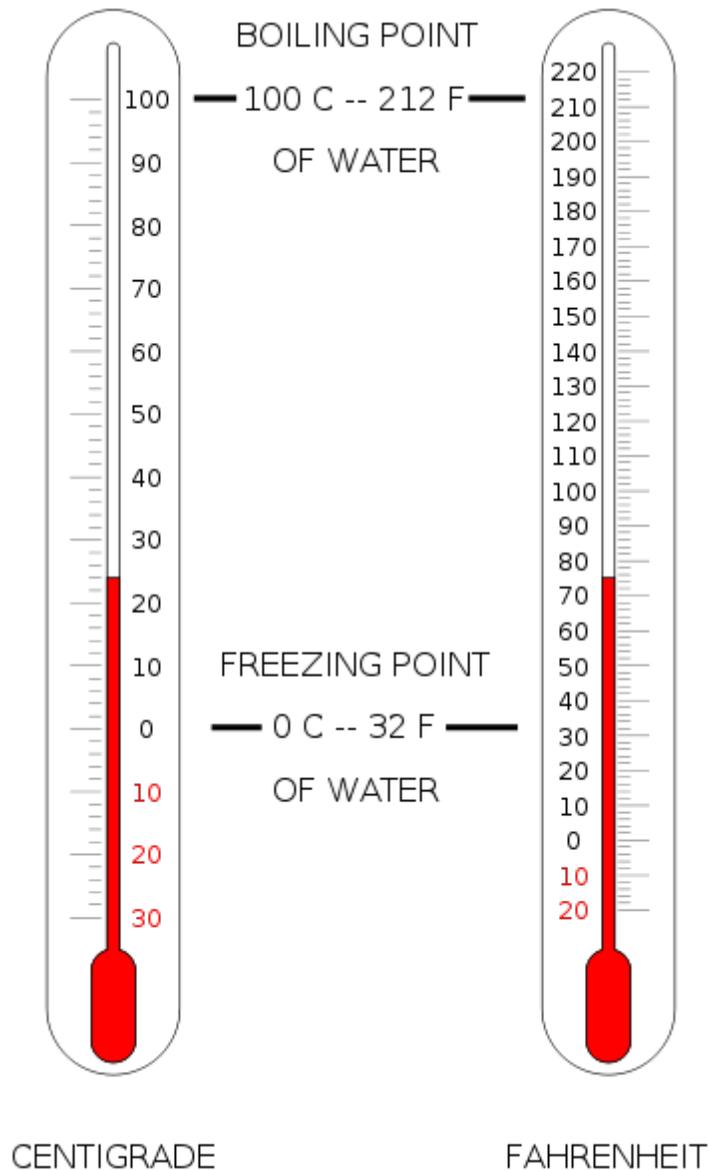
Energy in thermodynamics is calculated by multiplying the thermal potential by the amount of entropy found at that potential: temperature times entropy.

Entropy can be created by friction but not annihilated.

Amount of substance (or mole number)

A physical quantity introduced in chemistry; usually determined indirectly. If mass and substance type of the sample are known, then atomic- or molecular masses (taken from a periodic table, masses measured by mass spectrometry) give direct access to the value of the amount of substance. If specific molar values are given, then the amount of substance of a given sample may be determined by measuring volume, mass or concentration.

- Gas collecting tube gases



Thermometer

Temperature

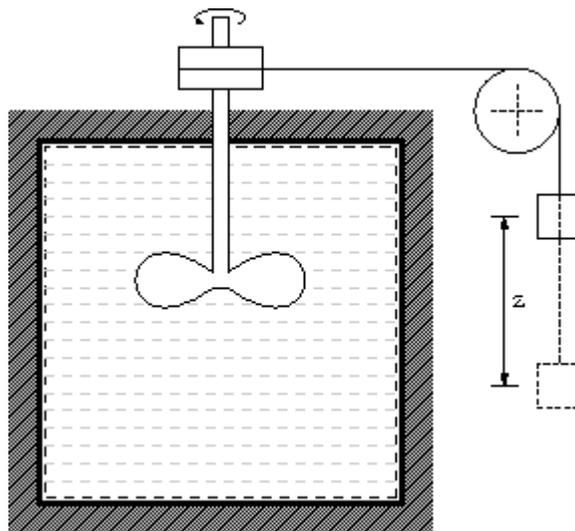
- Electromagnetic spectroscopy
- Galileo thermometer
- Gas thermometer principle: relation between temperature and volume or pressure of a gas (Gas laws).
 - constant pressure gas thermometer
 - constant volume gas thermometer
- Liquid crystal thermometer
- liquid thermometer principle: relation between temperature and volume of a liquid (Coefficient of thermal expansion).

- Alcohol thermometer
- Mercury-in-glass thermometer
- Pyranometer principle: solar radiation flux density relates to surface temperature (Stefan–Boltzmann law)
- Pyrometers principle: temperature dependence of spectral intensity of light (Planck's law), i.e. the color of the light relates to the temperature of its source, range: from about $-50\text{ }^{\circ}\text{C}$ to $+4000\text{ }^{\circ}\text{C}$, note: measurement of thermal radiation (instead of thermal conduction, or thermal convection) means: no physical contact becomes necessary in temperature measurement (pyrometry). Also note: thermal space resolution (images) found in Thermography.
- Resistance thermometer principle: relation between temperature and electrical resistance of metals (platinum) (Electrical resistance), range: 10 to 1,000 kelvins, application in physics and industry
- solid thermometer principle: relation between temperature and length of a solid (Coefficient of thermal expansion).
 - Bi-metallic strip
- Thermistors principle: relation between temperature and electrical resistance of ceramics or polymers, range: from about 0.01 to 2,000 kelvins (-273.14 to $1,700\text{ }^{\circ}\text{C}$)
- Thermocouples principle: relation between temperature and voltage of metal junctions, range: from about $-200\text{ }^{\circ}\text{C}$ to $+1350\text{ }^{\circ}\text{C}$
- Thermometer
- Thermopile is a set of connected thermocouples
- Triple Point cell used for calibrating thermometers.

Imaging technology

- Thermographic camera uses a microbolometer for detection of heat-radiation.

Energy carried by entropy or thermal energy



An active calorimeter lacking a temperature measurement device.

This includes thermal capacitance or temperature coefficient of energy, reaction energy, heat flow ... Calorimeters are called passive if gauged to measure emerging energy carried by entropy, for example from chemical reactions. Calorimeters are called active or heated if they heat the sample, or reformulated: if they are gauged to fill the sample with a defined amount of entropy.

- Actinometer measures the heating power of radiation.
- constant-temperature calorimeter, phase change calorimeter for example an ice calorimeter or any other calorimeter observing a phase change or using a gauged phase change for heat measurement.
- constant-volume calorimeter, also called bomb calorimeter
- constant-pressure calorimeter, enthalpy-meter or coffee cup calorimeter
- Differential Scanning Calorimeter
- Reaction calorimeter

Entropy

Entropy is accessible indirectly by measurement of energy and temperature.

Entropy transfer

Phase change calorimeter's energy value divided by absolute temperature give the entropy exchanged. Phase changes produce no entropy and therefore offer themselves as an entropy measurement concept. Thus entropy values occur indirectly by processing energy measurements at defined temperatures, without producing entropy.

- constant-temperature calorimeter, phase change calorimeter
- Heat flux sensor uses thermopiles which are connected thermocouples to determine current density or flux of entropy.

Entropy content

The given sample is cooled down to (almost) absolute zero (for example by submerging the sample in liquid helium). At absolute zero temperature any sample is assumed to contain no entropy. Then the following two active calorimeter types can be used to fill the sample with entropy until the desired temperature has been reached:

constant-pressure calorimeter, enthalpy-meter, active

- constant-temperature calorimeter, phase change calorimeter, active

Entropy production

Processes transferring energy from a non-thermal carrier to heat as a carrier do produce entropy (Example: mechanical/electrical friction, established by Count Rumford). Either

the produced entropy or heat are measured (calorimetry) or the transferred energy of the non-thermal carrier may be measured.

- calorimeter
- (any device for measuring the work which will or would eventually be converted to heat and the ambient temperature)

Entropy lowering its temperature—without losing energy—produces entropy (Example: Heat conduction in an isolated rod; "thermal friction").

- calorimeter

temperature coefficient of energy or "heat capacity"

Concerning a given sample, a proportionality factor relating temperature change and energy carried by heat. If the sample is a gas, then this coefficient depends significantly on being measured at constant volume or at constant pressure. (The terminology preference in the heading indicates that the classical use of heat bars it from having substance-like properties.)

- constant-volume calorimeter, bomb calorimeter
- constant-pressure calorimeter, enthalpy-meter

specific temperature coefficient of energy or "specific heat"

The temperature coefficient of energy divided by a substance-like quantity (amount of substance, mass, volume) describing the sample. Usually calculated from measurements by a division or could be measured directly using a unit amount of that sample.

Coefficient of thermal expansion

- Dilatometer
- Strain gauge

Melting temperature (of a solid)

- Thiele tube
- Kofler bench
- Differential Scanning Calorimeter gives melting point and enthalpy of fusion.

Boiling temperature (of a liquid)

- Ebullioscope a device for measuring the boiling point of a liquid. This device is also part of a method that uses the effect of boiling point elevation for calculating the molecular mass of a solvent.

More on continuum mechanics

This includes mostly instruments which measure macroscopic properties of matter: In the fields of solid state physics; in condensed matter physics which considers solids, liquids and in-betweens exhibiting for example viscoelastic behavior. Furthermore fluid mechanics, where liquids, gases, plasmas and in-betweens like supercritical fluids are studied.

Density

This refers to particle density of fluids and compact(ed) solids like crystals, in contrast to bulk density of grainy or porous solids.

- Aerometer liquids
- Dasymer gases
- Gas collecting tube gases
- Hydrometer liquids
- Pycnometer liquids
- resonant frequency and Damping Analyser (RFDA) solids

Hardness of a solid

- Durometer

Shape and surface of a solid

- Holographic interferometer
- Laser produced speckle pattern analysed.
- resonant frequency and Damping Analyser (RFDA)
- Tribometer

Deformation of condensed matter

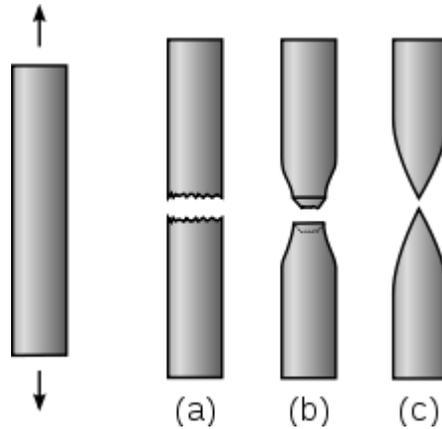
- Strain gauge all below

Elasticity of a solid (Elastic moduli)

- resonant frequency and Damping Analyser (RFDA), using the impulse excitation technique: A small mechanical impulse causes the sample to vibrate. The vibration depends on elastic properties, density, geometry and inner structures (lattice or fissures).

Plasticity of a solid

- Cam plastometer
- Plastometer



Measurement results (a) brittle (b) ductile with breaking point (c) ductile without breaking point.

Tensile strength, ductility or malleability of a solid

- Universal Testing Machine

Granularity of a solid or of a suspension

- Grindometer

Viscosity of a fluid

- Rheometer
- Viscometer

Optical activity

- Polarimeter

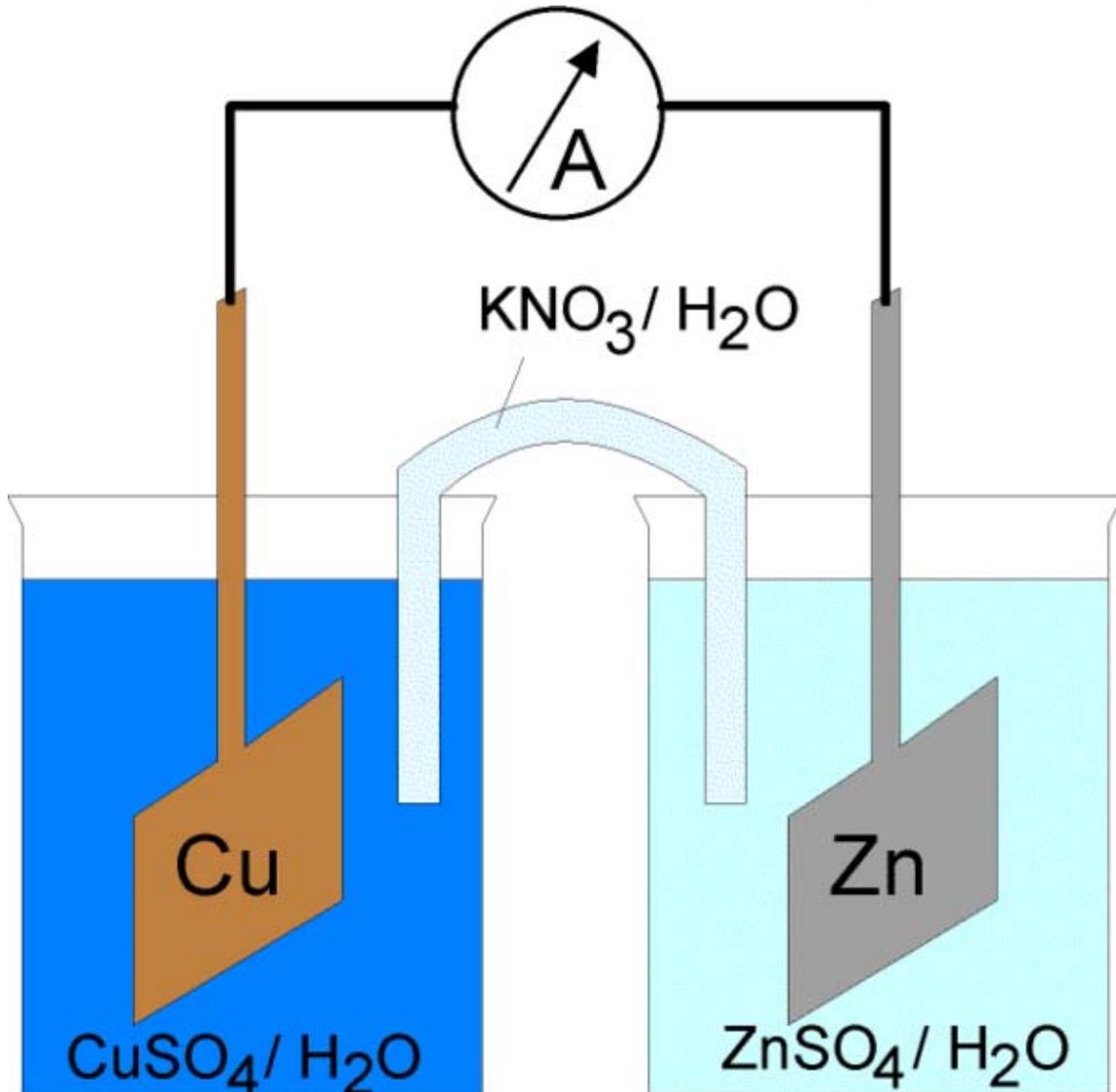
Surface tension of liquids

- Tensiometer

Imaging technology

- Tomograph, device and method for non-destructive analysis of multiple measurements done on a geometric object, for producing 2- or 3-dimensional images, representing the inner structure of that geometric object.
- Wind tunnel

More on electric properties of condensed matter, gas



The electrochemical cell: A device for measuring substance potentials.

Permittivity, relative static permittivity, (dielectric constant) or electric susceptibility

- Capacitor

Such measurements also allow to access values of molecular dipoles.

Magnetic susceptibility or magnetization

- Gouy balance

Substance potential or chemical potential or molar Gibbs energy

Phase conversions like changes of aggregate state, chemical reactions or nuclear reactions transmuting substances, from reactants to products, or diffusion through membranes have an overall energy balance. Especially at constant pressure and constant temperature molar energy balances define the notion of a substance potential or chemical potential or molar Gibbs energy, which gives the energetic information about whether the process is possible or not - in a closed system.

Energy balances that include entropy consist of two parts: A balance that accounts for the changed entropy content of the substances. And another one that accounts for the energy freed or taken by that reaction itself, the Gibbs energy change. The sum of reaction energy and energy associated to the change of entropy content is also called enthalpy. Often the whole enthalpy is carried by entropy and thus measurable calorimetrically.

For standard conditions in chemical reactions either molar entropy content and molar Gibbs energy with respect to some chosen zero point are tabulated. Or molar entropy content and molar enthalpy with respect to some chosen zero are tabulated.

The substance potential of a redox reaction is usually determined electrochemically current-free using reversible cells.

- Redox electrode

Other values may be determined indirectly by calorimetry. Also by analyzing phase-diagrams.

Sub-microstructural properties of condensed matter, gas

- Infrared spectroscopy
- Neutron detector
- Radio frequency spectrometers for Nuclear magnetic resonance and for Electron paramagnetic resonance
- Raman spectroscopy

Crystal structure

- An X-ray tube, a sample scattering the X-rays and a photographic plate to detect them. This constellation forms the scattering instrument used by X-ray crystallography for investigating crystal structures of samples. Amorphous solids lack a distinct pattern and are identifiable thereby.

Imaging technology, Microscope

- Electron microscope
 - Transmission electron microscope

- Optical microscope uses reflectiveness or refractiveness of light to produce an image.
- Scanning acoustic microscope
- Scanning probe microscope
 - Atomic force microscope (AFM)
 - Scanning electron microscope
 - Scanning tunneling microscope (STM)
- Focus variation
- X-ray microscope

Rays ("waves" and "particles")

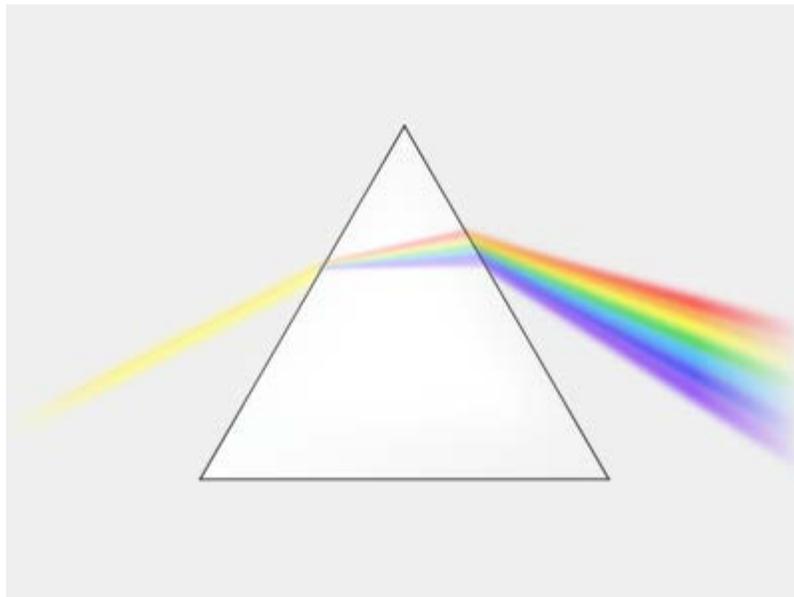
Sound, compression waves in matter

Microphones in general, sometimes their sensitivity is increased by the reflection- and concentration principle realized in acoustic mirrors.

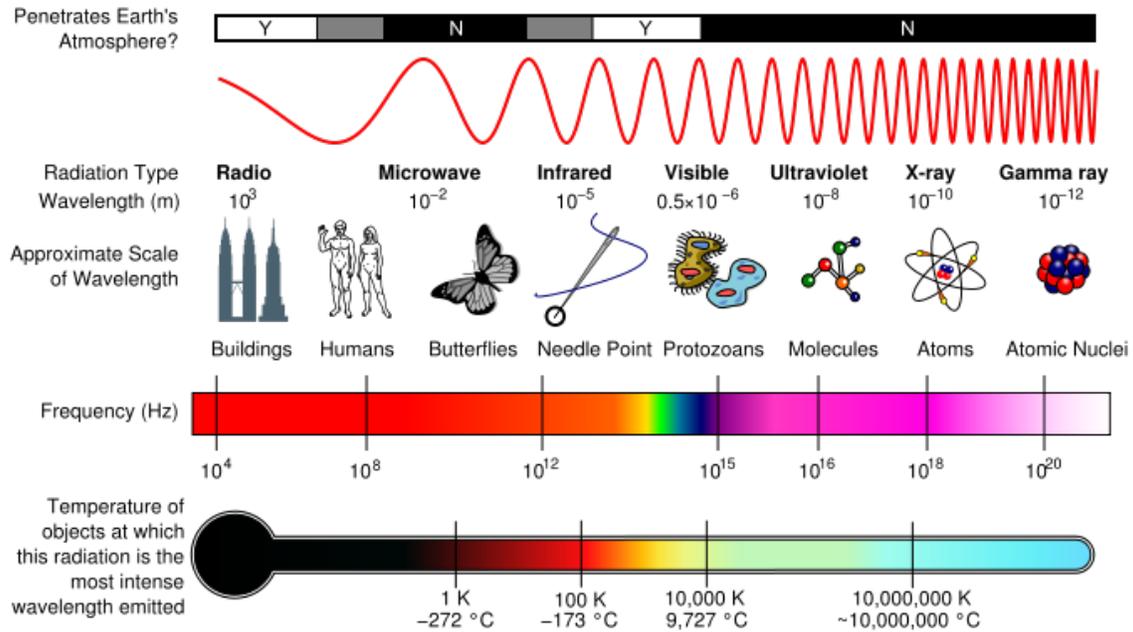
- Laser microphone
- Seismometer

Sound pressure

- microphone or hydrophone properly gauged
- Shock tube
- Sound level meter



A device for unmixing sun-light: the prism.



The electromagnetic spectrum

Light and radiation without a rest mass, non-ionizing

- Antenna (radio)
- bolometer measuring the energy of incident electromagnetic radiation.
- camera
- EMF meter
- Interferometer used in the wide field of Interferometry
- Optical power meter
- Microwave power meter
- Photographic plate
- Photomultiplier
- Phototube
- Radio telescope
- Spectrometer
- T-ray detectors

Photon polarization

- Polarizer

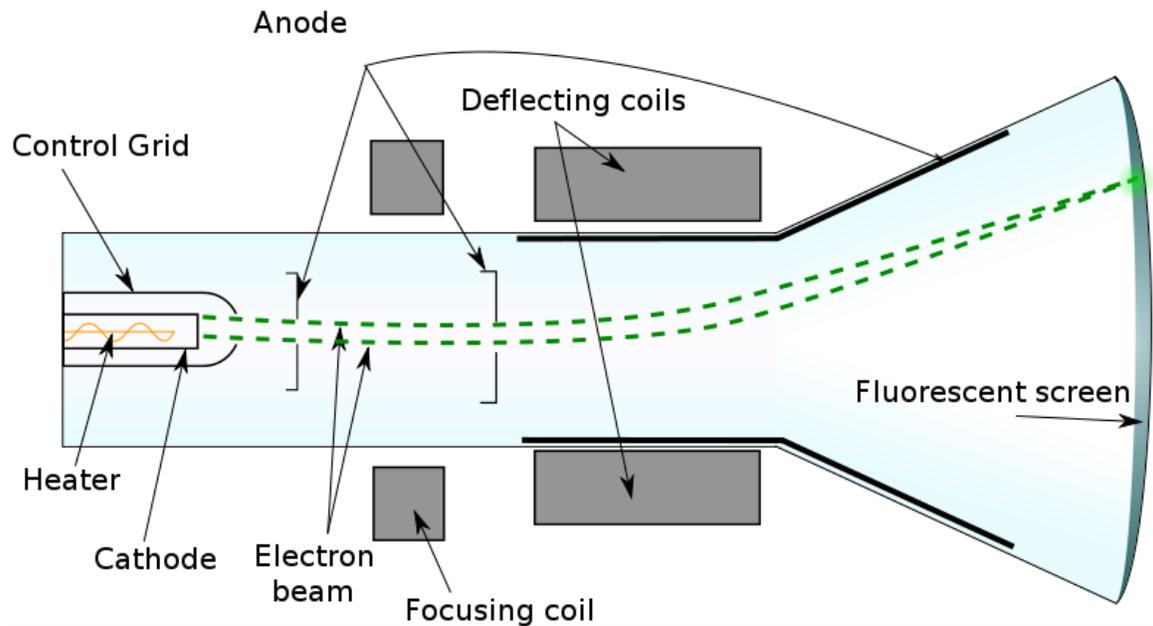
Pressure (current density of linear momentum)

- Nichols radiometer

radiant flux

The measure of the total power of light emitted.

- Integrating sphere for measuring the total radiant flux of a light source



A Cathode ray tube.

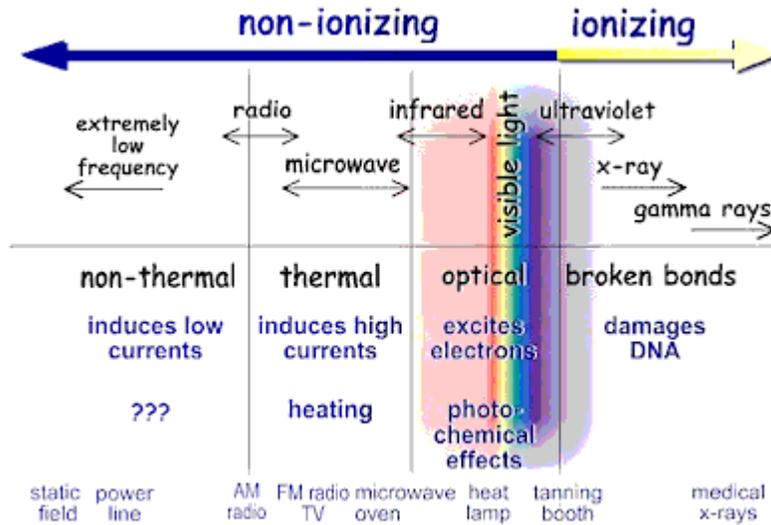
Radiation with a rest mass, particle radiation

Cathode ray

- Crookes tube
- Cathode ray tube, a phosphor coated anode

Atom polarization and electron polarization

- Stern-Gerlach experiment



Another visualization of the electromagnetic spectrum.

Ionizing radiation

Ionizing radiation includes rays of "particles" as well as rays of "waves". Especially X-rays and Gamma rays transfer enough energy in non-thermal, (single) collision processes to separate electron(s) from an atom.



A cloud chamber detecting alpha-rays.

particle flux

- Bubble chamber
- Cloud chamber
- Dosimeter, a technical device realizes different working principles.
- Geiger counter
- Microchannel plate detector
- Photographic plate
- Photostimulable phosphors
- Scintillation counter, Lucas cell
- Semiconductor detector

Identification and content

This could include chemical substances, rays of any kind, elementary particles, quasiparticles. Many measurement devices outside this section may be used or at least become part of an identification process.

Substance content in mixtures, substance identification

- Carbon dioxide sensor
- chromatographic device, gas chromatograph separates mixtures of substances. Different velocities of the substance types accomplish the separation.
- Colorimeter (measures absorbance, and thus concentration)
- gas detector
- Gas detector in combination with mass spectrometer,
- mass spectrometer identifies the chemical composition of a sample on the basis of the mass-to-charge ratio of charged particles.
- Nephelometer or turbidimeter
- oxygen sensor (= lambda sond)
- Refractometer, indirectly by determining the refractive index of a substance.
- Smoke detector
- Ultracentrifuge, separates mixtures of substances. In a force field of a centrifuge, substances of different densities separate.

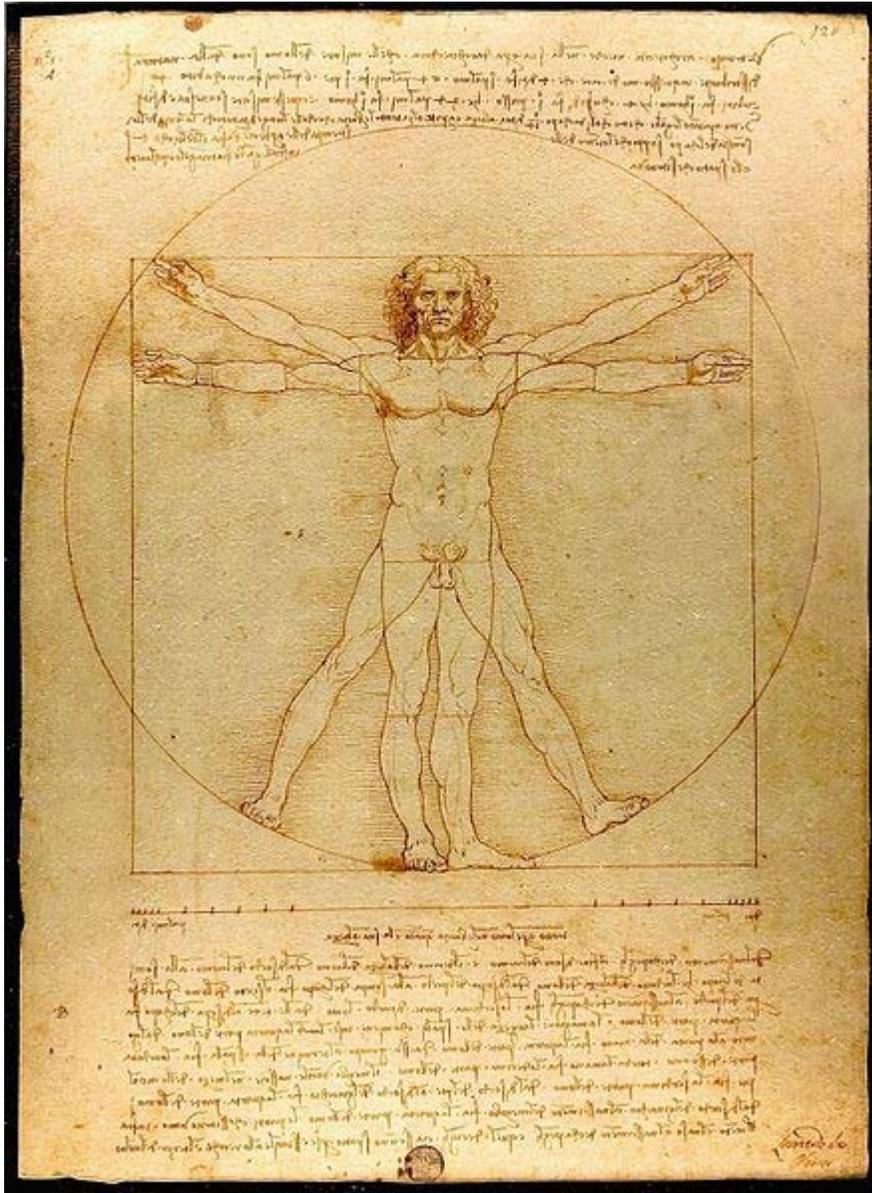
pH: Concentration of protons in a solution

- pH meter
- Saturated calomel electrode

Humidity

- Hygrometer measures the density of water in air
- Lysimeter measures the balance of water in soil

Human senses and human body



Vitruvian Man by Leonardo da Vinci, Gallerie dell'Accademia, Venice (1485-90)

Sight

Luminous flux, photometry

A measure of the perceived power of light, luminous flux is adjusted to reflect the varying sensitivity of the human eye to different wavelengths of light.

- Integrating sphere for measuring the total luminous flux of a light source

illuminance, photometry

- Densitometer
- Light meter
- Lux meter
- Photometer

Hearing

Loudness in phon

- Headphone, loudspeaker, sound pressure gauged, for measuring an equal-loudness contour of a human ear.
- Sound level meter calibrated to a equal-loudness contour of the human auditory system behind the human ear.

Temperature (sense and body)

Body temperature or Core temperature

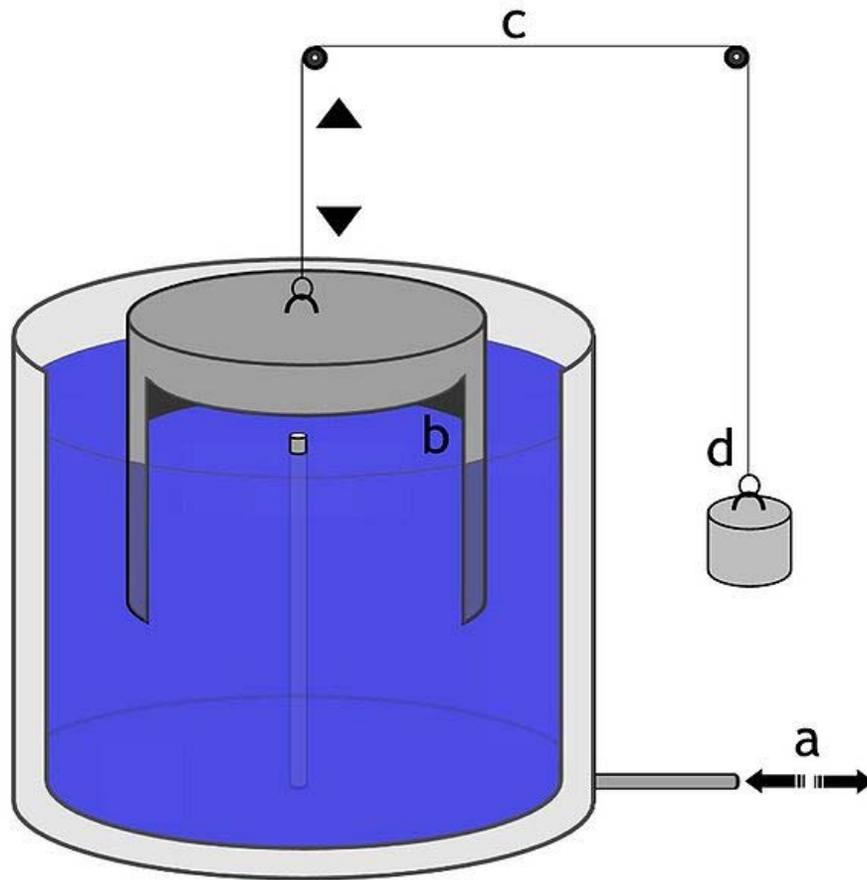
- Medical thermometer

circulatory system (mainly heart and blood vessels for distributing substances fast)

Blood-related parameters are listed in a blood test.

- Electrocardiograph records the electrical activity of the heart
- Glucose meter for obtaining the status of blood sugar.
- Sphygmomanometer, a blood pressure meter used to determine blood pressure in medicine.

Respiratory system (lung and airways controlling the breathing process)



A spirometer, inhaling into pipe a fills volume b, the rest balances forces.

- Spirometer

concentration or partial pressure of carbon dioxide in the respiratory gases

- Capnograph

nervous system (nerves transmitting and processing information electrically)

- Electroencephalograph records the electrical activity of the brain

musculoskeletal system (muscles and bones for movement)

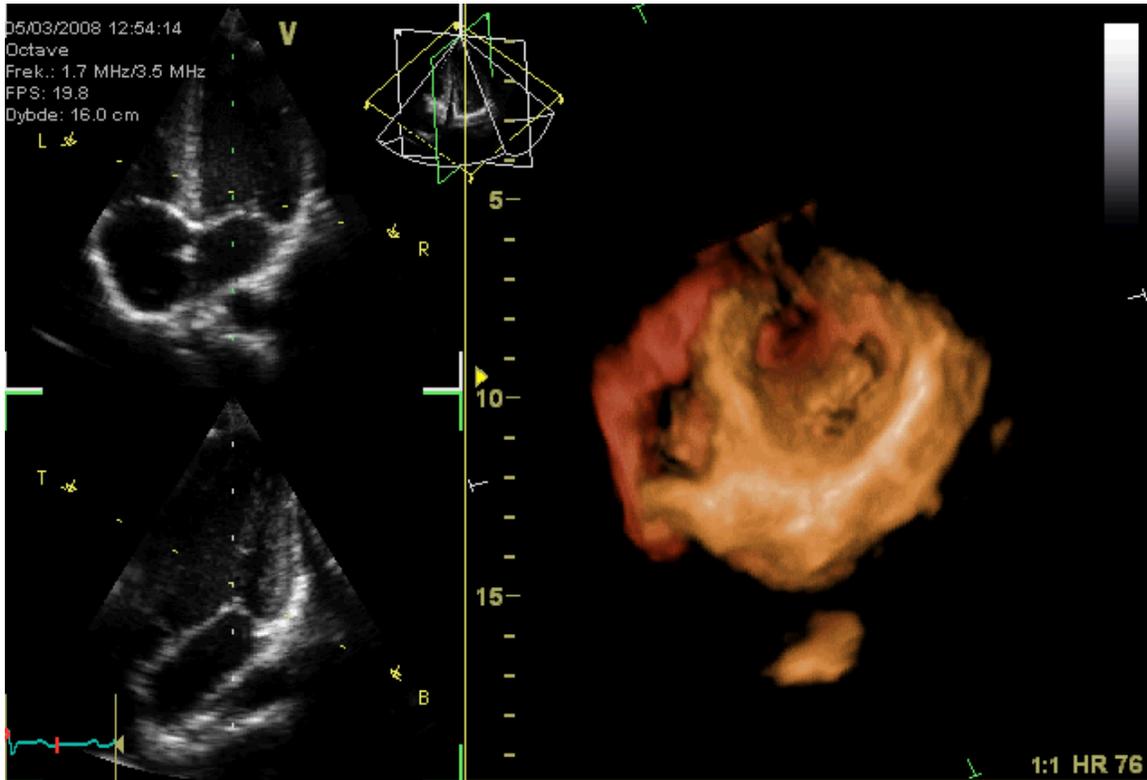
power, work of muscles

- Ergometer

metabolic system

- Body fat meter

Medical imaging



An echocardiogram processed into a three dimensional representation.

- Computed tomography
- Magnetic resonance imaging
- Medical ultrasonography
- Radiology
- Tomograph, device and method for non-destructive analysis of multiple measurements done on a geometric object, for producing 2- or 3-dimensional images, representing the inner structure of that geometric object.

Meteorology

Navigation and Surveying

Astronomy

- Radio antenna
- Telescope

Military

Some instruments, such as telescopes and sea navigation instruments, have had military applications for many centuries. However, the role of instruments in military affairs rose exponentially with the development of technology via applied science, which began in the mid-19th century and has continued through the present day. Military instruments as a class draw on most of the categories of instrument described throughout, such as navigation, astronomy, optics and imaging, and the kinetics of moving objects. Common abstract themes that unite military instruments are seeing into the distance, seeing in the dark, knowing an object's geographic location, and knowing and controlling a moving object's path and destination.

Special features of these instruments may include ease of use, speed, reliability and accuracy; nevertheless additionally one might hope seeing them as instruments whose existence, not use, ultimately helps in establishing a humane and humanistic peace between individual humans as well as groups of them.

Uncategorized, specialized, or generalized application

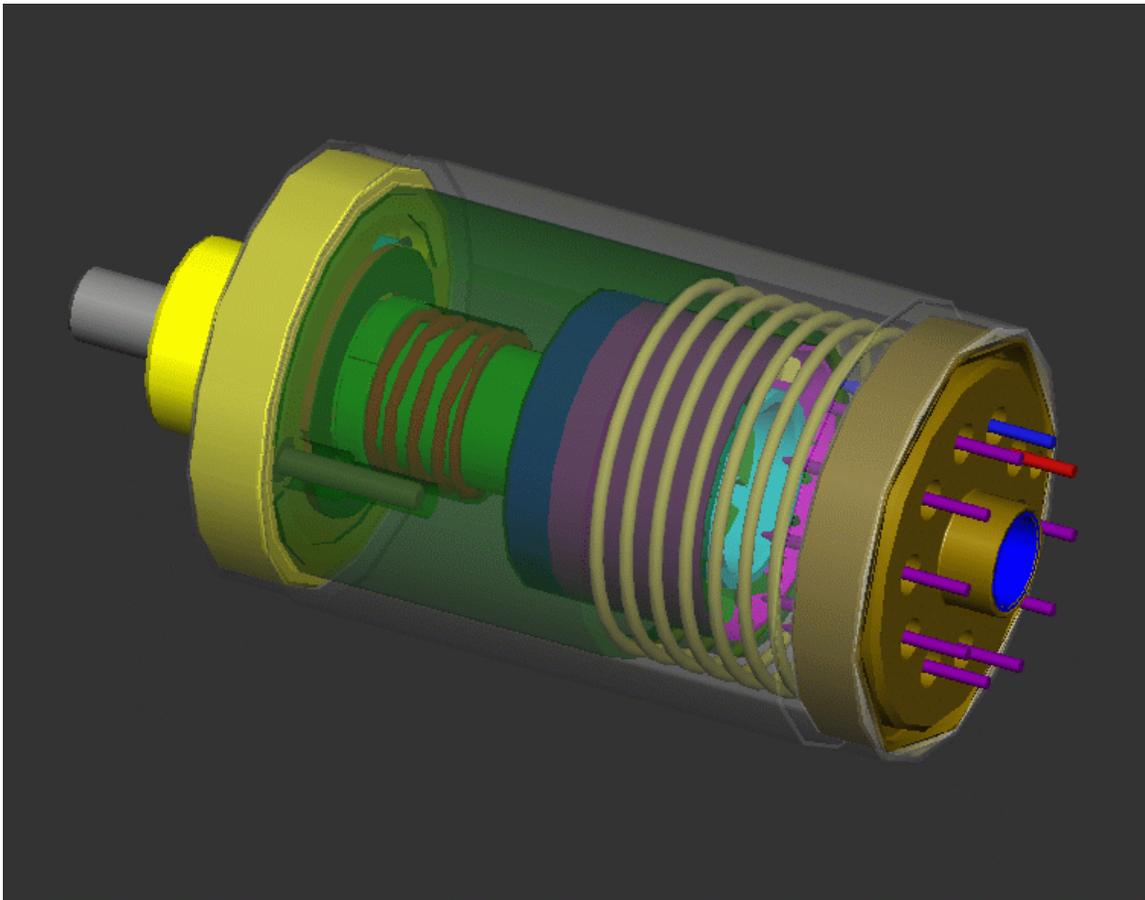
- Checkweigher measures precise weight of items in a conveyor line, rejecting under or overweight objects.
- Densitometer measures light transmission through processed photographic film or transparent material or light reflection from a reflective material.
- Force platform measures ground reaction force.
- Gauge (engineering) A highly precise measurement instrument, also usable to calibrate other instruments of the same kind. Often found in conjunction with defining or applying technical standards.
- Gradiometer any device that measures spatial variations of a physical quantity. For example as done in gravity gradiometry.
- Parking meter measures time a vehicle is parked at a particular spot, usually with a fee.
- Postage meter measures postage used from a prepaid account.
- S meter measures the signal strength processed by a communications receiver.
- Sensor, hypernym for devices that measure with little interaction, typically used in technical applications.
- Spectroscope is an important tool used by physicists.
- SWR meter check the quality of the match between the antenna and the transmission line.
- Time-domain reflectometer locates faults in metallic cables.
- Universal measuring machine measures geometric locations for inspecting tolerances.

Fictional devices

- Tricorder, a multipurpose scanning device, originating from the science-fictional Star Trek series.

Chapter 3

Accelerometer



A depiction of an accelerometer designed at Sandia National Laboratories.

An **accelerometer** is a device that measures the proper acceleration of the device. This is *not necessarily* the same as the coordinate acceleration (change of velocity of the device in space), but is rather the type of acceleration associated with the phenomenon of weight

experienced by a test mass that resides in the frame of reference of the accelerometer device. For an example of where these types of acceleration differ, an accelerometer will measure a value when sitting on the ground, because masses there have weights, even though they do not change velocity. However, an accelerometer in gravitational free fall toward the center of the Earth will measure a value of zero because, even though its speed is increasing, it is in an inertial frame of reference, in which it is weightless.

An accelerometer thus measures **weight per unit of (test) mass**, a quantity also known as specific force, or g-force. Another way of stating this is that by measuring weight, an accelerometer measures the acceleration of the free-fall reference frame (inertial reference frame) relative to itself.

Most accelerometers do not display the value they measure, but supply it to other devices. Real accelerometers also have practical limitations in how quickly they respond to changes in acceleration, and cannot respond to changes above a certain frequency of change.

Single- and multi-axis models of accelerometer are available to detect magnitude and direction of the proper acceleration (or g-force), as a vector quantity, and can be used to sense orientation (because direction of weight changes), coordinate acceleration (so long as it produces g-force or a change in g-force), vibration, shock, and falling (a case where the proper acceleration changes, since it tends toward zero). Micromachined accelerometers are increasingly present in portable electronic devices and video game controllers, to detect the position of the device or provide for game input.

Pairs of accelerometers extended over a region of space can be used to detect differences (gradients) in the proper accelerations of frames of references associated with those points. These devices are called gradiometers, as they measure gradients in the gravitational field. Such pairs of accelerometers in theory may also be able to detect gravity waves.

Physical principles

An accelerometer measures proper acceleration, which is the acceleration it experiences relative to freefall and is the acceleration felt by people and objects. Put another way, at any point in spacetime the equivalence principle guarantees the existence of a local inertial frame, and an accelerometer measures the acceleration relative to that frame. Such accelerations are popularly measured in terms of g-force.

An accelerometer at rest relative to the Earth's surface will indicate approximately 1 g *upwards*, because any point on the Earth's surface is accelerating upwards relative to the local inertial frame (the frame of a freely falling object near the surface). To obtain the acceleration due to motion with respect to the Earth, this "gravity offset" must be subtracted and corrections for effects caused by the Earth's rotation relative to the inertial frame.

The reason for the appearance of a gravitational offset is Einstein's equivalence principle, which states that the effects of gravity on an object are indistinguishable from acceleration. When held fixed in a gravitational field by, for example, applying a ground reaction force or an equivalent upward thrust, the reference frame for an accelerometer (its own casing) accelerates upwards with respect to a free-falling reference frame. The effects of this acceleration are indistinguishable from any other acceleration experienced by the instrument, so that an accelerometer cannot detect the difference between sitting in a rocket on the launch pad, and being in the same rocket in deep space while it uses its engines to accelerate at 1 g. For similar reasons, an accelerometer will read *zero* during any type of free fall. This includes use in a coasting spaceship in deep space far from any mass, a spaceship orbiting the Earth, an airplane in a parabolic "zero-g" arc, or any free-fall in vacuum. Another example is free-fall at a sufficiently high altitude that atmospheric effects can be neglected.

However this does not include a (non-free) fall in which air resistance produces drag forces that reduce the acceleration, until constant terminal velocity is reached. At terminal velocity the accelerometer will indicate 1 g acceleration upwards. For the same reason a skydiver, upon reaching terminal velocity, does not feel as though he or she were in "free-fall", but rather experiences a feeling similar to being supported (at 1 g) on a "bed" of uprushing air.

Acceleration is quantified in the SI unit metres per second per second (m/s^2), in the cgs unit gal (Gal), or popularly in terms of g-force (*g*).

For the practical purpose of finding the acceleration of objects with respect to the Earth, such as for use in an inertial navigation system, a knowledge of local gravity is required. This can be obtained either by calibrating the device at rest, or from a known model of gravity at the approximate current position.

Structure

Conceptually, an accelerometer behaves as a damped mass on a spring. When the accelerometer experiences an acceleration, the mass is displaced to the point that the spring is able to accelerate the mass at the same rate as the casing. The displacement is then measured to give the acceleration.

In commercial devices, piezoelectric, piezoresistive and capacitive components are commonly used to convert the mechanical motion into an electrical signal. Piezoelectric accelerometers rely on piezoceramics (e.g. lead zirconate titanate) or single crystals (e.g. quartz, tourmaline). They are unmatched in terms of their upper frequency range, low packaged weight and high temperature range. Piezoresistive accelerometers are preferred in high shock applications. Capacitive accelerometers typically use a silicon micro-machined sensing element. Their performance is superior in the low frequency range and they can be operated in servo mode to achieve high stability and linearity.

Modern accelerometers are often small *micro electro-mechanical systems* (MEMS), and are indeed the simplest MEMS devices possible, consisting of little more than a cantilever beam with a proof mass (also known as seismic mass). Damping results from the residual gas sealed in the device. As long as the Q-factor is not too low, damping does not result in a lower sensitivity.

Under the influence of external accelerations the proof mass deflects from its neutral position. This deflection is measured in an analog or digital manner. Most commonly, the capacitance between a set of fixed beams and a set of beams attached to the proof mass is measured. This method is simple, reliable, and inexpensive. Integrating piezoresistors in the springs to detect spring deformation, and thus deflection, is a good alternative, although a few more process steps are needed during the fabrication sequence. For very high sensitivities quantum tunneling is also used; this requires a dedicated process making it very expensive. Optical measurement has been demonstrated on laboratory scale.

Another, far less common, type of MEMS-based accelerometer contains a small heater at the bottom of a very small dome, which heats the air inside the dome to cause it to rise. A thermocouple on the dome determines where the heated air reaches the dome and the deflection off the center is a measure of the acceleration applied to the sensor.

Most micromechanical accelerometers operate *in-plane*, that is, they are designed to be sensitive only to a direction in the plane of the die. By integrating two devices perpendicularly on a single die a two-axis accelerometer can be made. By adding an additional *out-of-plane* device three axes can be measured. Such a combination always has a much lower misalignment error than three discrete models combined after packaging.

Micromechanical accelerometers are available in a wide variety of measuring ranges, reaching up to thousands of g's. The designer must make a compromise between sensitivity and the maximum acceleration that can be measured.

Applications

Engineering

Accelerometers can be used to measure vehicle acceleration. They allow for performance evaluation of both the engine/drive train and the braking systems.

Accelerometers can be used to measure vibration on cars, machines, buildings, process control systems and safety installations. They can also be used to measure seismic activity, inclination, machine vibration, dynamic distance and speed with or without the influence of gravity. Applications for accelerometers that measure gravity, wherein an accelerometer is specifically configured for use in gravimetry, are called gravimeters.

Notebook computers equipped with accelerometers can contribute to the *Quake-Catcher Network* (QCN), a BOINC project aimed at scientific research of earthquakes.

Biology

Accelerometers are also increasingly used in the biological sciences. High frequency recordings of bi-axial or tri-axial acceleration (>10 Hz) allows the discrimination of behavioral patterns while animals are out of sight. Furthermore, recordings of acceleration allow researchers to quantify the rate at which an animal is expending energy in the wild, by either determination of limb-stroke frequency or measures such as overall dynamic body acceleration. Such approaches have mostly been adopted by marine scientists due to an inability to study animals in the wild using visual observations, however an increasing number of terrestrial biologists are adopting similar approaches. This device can be connected to an amplifier to amplify the signal.

Industry - Machinery Health Monitoring

Accelerometers are also used for machinery health monitoring of rotating equipment such as pumps, fans, rollers, compressors, and cooling towers,. Vibration monitoring programs are proven to save money, reduce downtime, and improve safety in plants worldwide by detecting conditions such as shaft misalignment, rotor imbalance, gear failure or bearing fault which can lead to costly repairs. Accelerometer vibration data allows the user to monitor machines and detect these faults before the rotating equipment fails. Vibration monitoring programs are utilized in industries such as automotive manufacturing, machine tool applications, pharmaceutical production, power generation and power plants, pulp and paper, food and beverage production, water and wastewater, hydropower, petrochemical and steel manufacturing.

Building and structural monitoring

Accelerometers are used to measure the motion and vibration of a structure that is exposed to dynamic loads. Dynamic loads originate from a variety of sources including:

- Human activities - walking, running, dancing or skipping
- Working machines - inside a building or in the surrounding area
- Construction work - driving piles, demolition, drilling and excavating
- Moving loads on bridges
- Vehicle collisions
- Impact loads - falling debris
- Concussion loads - internal and external explosions
- Collapse of structural elements
- Wind loads and wind gusts
- Air blast pressure
- Loss of support because of ground failure
- Earthquakes and aftershocks

Measuring and recording how a structure responds to these inputs is critical for assessing the safety and viability of a structure. This type of monitoring is called Dynamic Monitoring.

Medical applications

Zoll's AED Plus uses CPR-D•padz which contain an accelerometer to measure the depth of CPR chest compressions.

Within the last several years, Nike, Polar and other companies have produced and marketed sports watches for runners that include footpods, containing accelerometers to help determine the speed and distance for the runner wearing the unit.

In Belgium, accelerometer-based step counters are promoted by the government to encourage people to walk a few thousand steps each day.

Herman Digital Trainer uses accelerometers to measure strike force in physical training.

Navigation

An **Inertial Navigation System** (INS) is a navigation aid that uses a computer and motion sensors (accelerometers) to continuously calculate via dead reckoning the position, orientation, and velocity (direction and speed of movement) of a moving object without the need for external references. Other terms used to refer to inertial navigation systems or closely related devices include **inertial guidance system**, **inertial reference platform**, and many other variations.

An accelerometer alone is unsuitable to determine changes in altitude over distances where the vertical decrease of gravity is significant, such as for aircraft and rockets. In the presence of a gravitational gradient, the calibration and data reduction process is numerically unstable.

Transport

Accelerometers are used to detect apogee in both professional and in amateur rocketry.

Accelerometers are also being used in Intelligent Compaction rollers. Accelerometers are used alongside gyroscopes in inertial guidance systems.

One of the most common uses for MEMS accelerometers is in airbag deployment systems for modern automobiles. In this case the accelerometers are used to detect the rapid negative acceleration of the vehicle to determine when a collision has occurred and the severity of the collision. Another common automotive use is in electronic stability control systems, which use a lateral accelerometer to measure cornering forces. The widespread use of accelerometers in the automotive industry has pushed their cost down dramatically. Another automotive application is the monitoring of noise, vibration and

harshness (NVH), conditions that cause discomfort for drivers and passengers and may also be indicators of mechanical faults.

Tilting trains use accelerometers and gyroscopes to calculate the required tilt.

Vulcanology

Modern electronic accelerometers are used in remote sensing devices intended for the monitoring of active volcanos to detect the motion of magma

Consumer electronics

Accelerometers are increasingly being incorporated into personal electronic devices.

Motion input

Some smartphones, digital audio players and personal digital assistants contain accelerometers for user interface control; often the accelerometer is used to present landscape or portrait views of the device's screen, based on the way the device is being held.

Smartphones can download an Automatic Collision Notification (ACN) app such as My-911, similar to the Onstar AACN service, Ford Link's 911 Assist, Toyota's Safety Connect, Lexus Link, or BMW Assist. The phone's accelerometer detects crash-strength G-forces and automatically calls for assistance unless manually cancelled.

Nintendo's Wii video game console uses a controller called a Wii Remote that contains a three-axis accelerometer and was designed primarily for motion input. Users also have the option of buying an additional motion-sensitive attachment, the Nunchuk, so that motion input could be recorded from both of the user's hands independently.

The Sony PlayStation 3 uses the DualShock 3 remote which uses a six-axis accelerometer that can be used to make steering more realistic in racing games, such as Motorstorm and Burnout Paradise.

The Nokia 5500 sport features a 3D accelerometer that can be accessed from software. It is used for step recognition (counting) in a sport application, and for tap gesture recognition in the user interface. Tap gestures can be used for controlling the music player and the sport application, for example to change to next song by tapping through clothing when the device is in a pocket. Other uses for accelerometer in Nokia phones include Pedometer functionality in Nokia Sports Tracker. Some other devices provide the tilt sensing feature with a cheaper component, which is not a true accelerometer.

Sleep phase alarm clocks use accelerometric sensors to detect movement of a sleeper, so that it can wake the person when he/she is not in REM phase, therefore awakes more easily.

Orientation sensing

A number of 21st century devices use accelerometers to align the screen depending on the direction the device is held, i.e. switching between portrait and landscape modes. Such devices include many tablet PCs and some smartphones and digital cameras.

For example, Apple uses an LIS302DL accelerometer in the iPhone, iPod Touch and the 4th&5th generation iPod Nano allowing the device to know when it is tilted on its side. Third-party developers have expanded its use with fanciful applications such as electronic bobbleheads. The BlackBerry Storm phone was also an early user of this orientation sensing feature.

The Nokia N95 and Nokia N82 have accelerometers embedded inside them. It was primarily used as a tilt sensor for tagging the orientation to photos taken with the built-in camera, later thanks to a firmware update it became available to other applications.

As of January 2009, almost all new mobile phones and digital cameras contain at least a tilt sensor (sometimes an accelerometer) for the purpose of auto image rotation, motion-sensitive mini-games, and to correct shake when taking photographs.

Image stabilization

Camcorders use accelerometers for image stabilization. Still cameras use accelerometers for anti-blur capturing. The camera holds off snapping the CCD "shutter" when the camera is moving. When the camera is still (if only for a millisecond, as could be the case for vibration), the CCD is "snapped". An example application which has used such technology is the Glogger VS2, a phone application which runs on Symbian OS based phone with accelerometer such as Nokia N96. Some digital cameras, contain accelerometers to determine the orientation of the photo being taken and also for rotating the current picture when viewing.

Device integrity

Many laptops feature an accelerometer which is used to detect drops. If a drop is detected, the heads of the hard disk are parked to avoid data loss and possible head or disk damage by the ensuing shock.

Gravimetry

A **gravimeter** or gravitometer, is an instrument used in gravimetry for measuring the local gravitational field. A gravimeter is a type of accelerometer, except that accelerometers are susceptible to all vibrations including noise, that cause oscillatory accelerations. This is counteracted in the gravimeter by integral vibration isolation and signal processing. Though the essential principle of design is the same as in accelerometers, gravimeters are typically designed to be much more sensitive than accelerometers in order to measure very tiny changes within the Earth's gravity, of 1 g. In

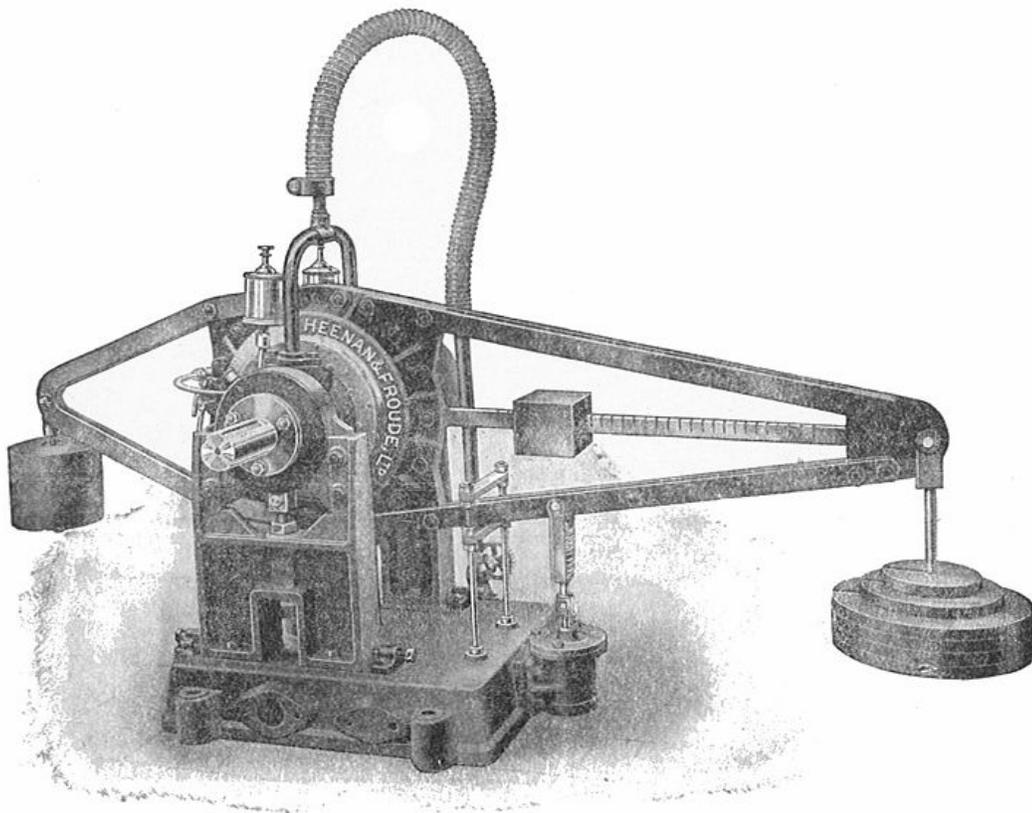
contrast, other accelerometers are often designed to measure 1000 g or more, and many perform multi-axial measurements. The constraints on temporal resolution are usually less for gravimeters, so that resolution can be increased by processing the output with a longer "time constant".

Types of accelerometer

- Piezoelectric accelerometer
- Shear mode accelerometer
- Surface micromachined capacitive (MEMS)
- Thermal (submicrometre CMOS process)
- Bulk micromachined capacitive
- Bulk micromachined piezoelectric resistive
- Capacitive spring mass base
- Electromechanical servo (Servo Force Balance)
- Null-balance
- Strain gauge
- Resonance
- Magnetic induction
- Optical
- Surface acoustic wave (SAW)
- Laser accelerometer
- DC response
- High temperature
- Low frequency
- High gravity
- Triaxial
- Modally tuned impact hammers
- Seat pad accelerometers
- Pendulating integrating gyroscopic accelerometer

Chapter 4

Dynamometer



Early hydraulic dynamometer, with dead-weight torque measurement.

A **dynamometer** or "**dyno**" for short, is a device for measuring force, moment of force (torque), or power. For example, the power produced by an engine, motor or other rotating prime mover can be calculated by simultaneously measuring torque and rotational speed (RPM).

A dynamometer can also be used to determine the torque and power required to operate a driven machine such as a pump. In that case, a *motoring* or *driving* dynamometer is used. A dynamometer that is designed to be driven is called an *absorption* or *passive* dynamometer. A dynamometer that can either drive or absorb is called a *universal* or *active* dynamometer.

In addition to being used to determine the torque or power characteristics of a machine under test (MUT), dynamometers are employed in a number of other roles. In standard emissions testing cycles such as those defined by the US Environmental Protection Agency (US EPA), dynamometers are used to provide simulated road loading of either the engine (using an engine dynamometer) or full powertrain (using a chassis dynamometer). In fact, beyond simple power and torque measurements, dynamometers can be used as part of a testbed for a variety of engine development activities such as the calibration of engine management controllers, detailed investigations into combustion behavior and tribology.

In the medical terminology, hand dynamometers are used for routine screening of grip strength and initial and ongoing evaluation of patients with hand trauma and dysfunction. They are also used to measure grip strength in patients where compromise of the cervical nerve roots or peripheral nerves is suspected.

In the rehabilitation, kinesiology, and ergonomics realms, force dynamometers are used for measuring the back, grip, arm, and/or leg strength of athletes, patients, and workers to evaluate physical status, performance, and task demands. Typically the force applied to a lever or through a cable are measured and then converted to a moment of force by multiplying by the perpendicular distance from the force to the axis of the level.

Principles of operation of torque power (absorbing) dynamometers

An absorbing dynamometer acts as a load that is driven by the prime mover that is under test (e.g. Pelton wheel). The dynamometer must be able to operate at any speed and load to any level of torque that the test requires.

Absorbing dynamometers are not to be confused with "inertia" dynamometers, which calculate power solely by measuring power required to accelerate a known mass drive roller and provide no variable load to the prime mover.

An Absorption dynamometer is usually equipped with some means of measuring the operating torque and speed.

The dynamometer's Power Absorption Unit absorbs the power developed by the prime mover. The power absorbed by the dynamometer is converted into heat and the heat generally dissipates into the ambient air or transfers to cooling water that dissipates into the air. Regenerative dynamometers, in which the prime mover drives a DC motor as a generator to create load, make excess DC power and potentially, using a DC/AC inverter,

can feed AC power back into the commercial electrical power grid - where the power produced is eventually converted back into heat (as in an oven or light bulb, etc.).

Absorption dynamometers can be equipped with two types of control systems to provide different main test types.

Constant Force

The dynamometer has a "braking" torque regulator, the PAU (Power Absorption Unit) is configured to provide a set braking force torque load while the prime mover is configured to operate at whatever throttle opening, fuel delivery rate or any other variable it is desired to test. The prime mover is then allowed to accelerate the engine through the desired speed or RPM range. Constant Force test routines require the PAU to be set slightly torque deficient as referenced to prime mover output to allow some rate of acceleration. Power is calculated based on torque x RPM / 5252 + calculated power required for the acceleration rate that occurred.

Constant Speed

If the dynamometer has a speed regulator (human or computer), the PAU provides a variable amount of braking force (torque) that is necessary to cause the prime mover to operate at the desired single test speed or RPM. The PAU braking load applied to the prime mover can be manually controlled or determined by a computer. Most systems employ eddy current, oil hydraulic or DC motor produced loads because of their linear and quick load change ability.

Power is calculated based on torque x RPM / 5252.

A motoring dynamometer acts as a motor that drives the equipment under test. It must be able to drive the equipment at any speed and develop any level of torque that the test requires. In common usage, AC or DC motors are used to drive the equipment or "load" device.

In most dynamometers power (P) is not measured directly; it must be calculated from torque (τ) and angular velocity (ω) values or force (F) and linear velocity (v):

$$P = \tau \cdot \omega$$

or

$$P = F \cdot v$$

where

P is the power in watts

τ is the torque in newton metres

ω is the angular velocity in radians per second

F is the force in newtons

v is the linear velocity in metres per second

Division by a conversion constant may be required depending on the units of measure used.

For imperial units,

$$P_{hp} = \frac{\tau_{lb\cdot ft} \cdot \omega_{rpm}}{5252}$$

where

P_{hp} is the power in horsepower

$\tau_{lb\cdot ft}$ is the torque in pound-feet

ω_{RPM} is the rotational velocity in revolutions per minute

For metric units,

$$P_{kW} = \frac{\tau_{N\cdot m} \cdot \omega_{rpm}}{9549}$$

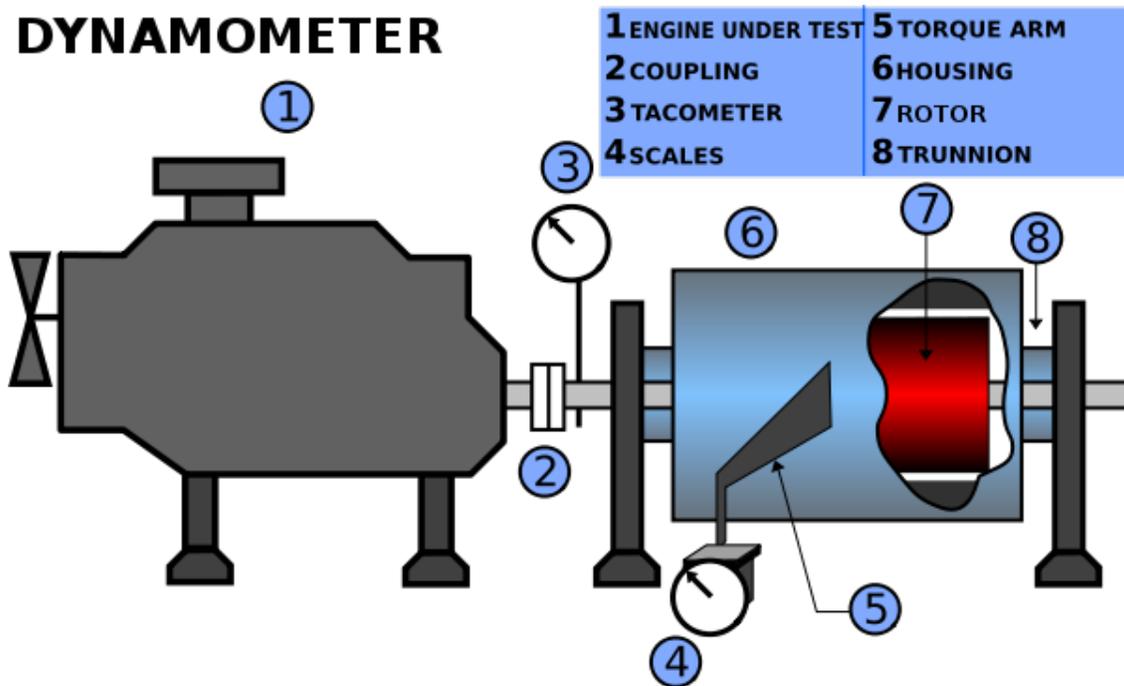
where

P_{kW} is the power in kilowatts

$\tau_{N\cdot m}$ is the torque in newton metres

ω_{rpm} is the rotational velocity in revolutions per minute

Detailed dynamometer description



Electrical dynamometer setup showing engine, torque measurement arrangement and tachometer

A dynamometer consists of an absorption (or absorber/driver) unit, and usually includes a means for measuring torque and rotational speed. An absorption unit consists of some type of rotor in a housing. The rotor is coupled to the engine or other equipment under

test and is free to rotate at whatever speed is required for the test. Some means is provided to develop a braking torque between dynamometer's rotor and housing. The means for developing torque can be frictional, hydraulic, electromagnetic etc. according to the type of absorption/driver unit.

One means for measuring torque is to mount the dynamometer housing so that it is free to turn except that it is restrained by a torque arm. The housing can be made free to rotate by using trunnions connected to each end of the housing to support the dynamometer in pedestal mounted trunnion bearings. The torque arm is connected to the dynamometer housing and a weighing scale is positioned so that it measures the force exerted by the dynamometer housing in attempting to rotate. The torque is the force indicated by the scales multiplied by the length of the torque arm measured from the center of the dynamometer. A load cell transducer can be substituted for the scales in order to provide an electrical signal that is proportional to torque.

Another means for measuring torque is to connect the engine to the dynamometer through a torque sensing coupling or torque transducer. A torque transducer provides an electrical signal that is proportional to torque.

With electrical absorption units, it is possible to determine torque by measuring the current drawn (or generated) by the absorber/driver. This is generally a less accurate method and not much practiced in modern times, but it may be adequate for some purposes.

When torque and speed signals are available, test data can be transmitted to a data acquisition system rather than being recorded manually. Speed and torque signals can also be recorded by a chart recorder or plotter.

Types of dynamometers

In addition to classification as *Absorption*, *Motoring* or *Universal* as described above, dynamometers can be classified in other ways.

A dynamometer that is coupled directly to an engine is known as an *engine dynamometer*.

A dynamometer that can measure torque and power delivered by the power train of a vehicle directly from the drive wheel or wheels (without removing the engine from the frame of the vehicle), is known as a *chassis dynamometer*.

Dynamometers can also be classified by the type of absorption unit or absorber/driver that they use. Some units that are capable of absorption only can be combined with a motor to construct an absorber/driver or universal dynamometer. The following types of absorption/driver units have been used:

Types of absorption/driver units

- Eddy current or electromagnetic brake (absorption only)
- Magnetic Powder brake (absorption only)
- Hysteresis Brake (absorption only)
- Electric motor/generator (absorb or drive)
- Fan brake (absorption only)
- Hydraulic brake (absorption only)
- Mechanical friction brake or Prony brake (absorption only)
- Water brake (absorption only)
- Compound dyno (usually an absorption dyno in tandem with an electric/motoring dyno)

Eddy current type absorber

EC dynamometers are currently the most common absorbers used in modern chassis dynos. The EC absorbers provide the quick load change rate for rapid load settling. Most are air cooled, but some are designed to require external water cooling systems.

Eddy current dynamometers require an electrically conductive core, shaft or disc, moving across a magnetic field to produce resistance to movement. Iron is a common material, but copper, aluminum and other conductive materials are usable.

In current (2009) applications, most EC brakes use cast iron discs, similar to vehicle disc brake rotors, and use variable electromagnets to change the magnetic field strength to control the amount of braking.

The electromagnet voltage is usually controlled by a computer, using changes in the magnetic field to match the power output being applied.

Sophisticated EC systems allow steady state and controlled acceleration rate operation.

Powder dynamometer

A powder dynamometer is similar to an eddy current dynamometer, but a fine magnetic powder is placed in the air gap between the rotor and the coil. The resulting flux lines create "chains" of metal particulate that are constantly built and broken apart during rotation creating great torque. Powder dynamometers are typically limited to lower RPM due to heat dissipation issues.

Hysteresis dynamometers

Hysteresis dynamometers, use a steel rotor that is moved through flux lines generated between magnetic pole pieces. This design, as in the usual "disc type" eddy current absorbers, allows for full torque to be produced at zero speed, as well as at full speed. Heat dissipation is assisted by forced air. Hysteresis and "disc type" EC dynamometers

are one of the most efficient technologies in small (200 hp (150 kW) and less) dynamometers. A hysteresis brake is an eddy current absorber that, unlike most "disc type" eddy current absorbers, puts the electromagnet coils inside a vented and ribbed cylinder and rotates the cylinder, instead of rotating a disc between electromagnets. The potential benefit for the hysteresis absorber is that the diameter can be decreased and operating RPM of the absorber may be increased.

Electric motor/generator dynamometer

Electric motor/generator dynamometers are a specialized type of adjustable-speed drives. The absorption/driver unit can be either an alternating current (AC) motor or a direct current (DC) motor. Either an AC motor or a DC motor can operate as a generator that is driven by the unit under test or a motor that drives the unit under test. When equipped with appropriate control units, electric motor/generator dynamometers can be configured as universal dynamometers. The control unit for an AC motor is a variable-frequency drive and the control unit for a DC motor is a DC drive. In both cases, regenerative control units can transfer power from the unit under test to the electric utility. Where permitted, the operator of the dynamometer can receive payment (or credit) from the utility for the returned power.

In engine testing, universal dynamometers can not only absorb the power of the engine but also, drive the engine for measuring friction, pumping losses and other factors.

Electric motor/generator dynamometers are generally more costly and complex than other types of dynamometers.

Fan brake

A fan is used to blow air to provide engine load. Changing gearing or fan or simply measuring the max RPM attained.

Hydraulic brake

The hydraulic brake system consists of a hydraulic pump (usually a gear type pump), a fluid reservoir and piping between the two parts. Inserted in the piping is an adjustable valve and between the pump and the valve is a gauge or other means of measuring hydraulic pressure. Usually, the fluid used was hydraulic oil, but recent synthetic multi-grade oils may be a better choice. In simplest terms, the engine is brought up to the desired RPM and the valve is incrementally closed and as the pumps outlet is restricted, the load increases and the throttle is simply opened until at the desired throttle opening. Unlike most other systems, power is calculated by factoring flow volume (calculated from pump design specs), hydraulic pressure and RPM. Brake HP, whether figured with pressure, volume and RPM or with a different load cell type brake dyno, should produce essentially identical power figures. Hydraulic dynos are renowned for having the absolute quickest load change ability, just slightly surpassing the eddy current absorbers. The

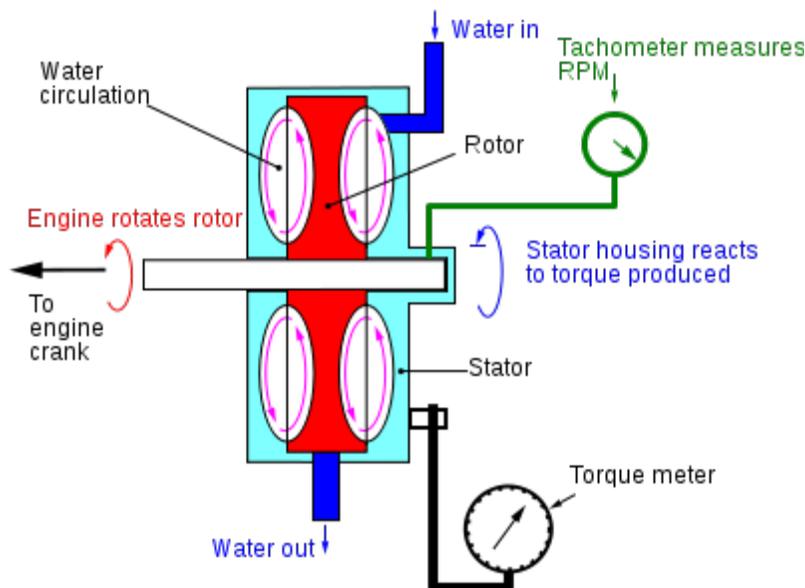
downside is that they require large quantities of hot oil under high pressure and the requirement for an oil reservoir.

Water brake type absorber

The water brake absorber is sometimes mistakenly called a "hydraulic dynamometer." Water brake absorbers are relatively common, having been manufactured for many years and noted for their high power capability, small package, light weight, and relatively low manufacturing cost as compared to other, quicker reacting "power absorber" types.

Their drawbacks are that they can take a relatively long period of time to "stabilize" their load amount and the fact that they require a constant supply of water to the "water brake housing" for cooling. In many parts of the country, environmental regulations now prohibit "flow through" water and large water tanks must be installed to prevent contaminated water from entering the environment.

The schematic shows the most common type of water brake, the variable level type. Water is added until the engine is held at a steady RPM against the load. Water is then kept at that level and replaced by constant draining and refilling, which is needed to carry away the heat created by absorbing the horsepower. The housing attempts to rotate in response to the torque produced but is restrained by the scale or torque metering cell that measures the torque.



This schematic shows a water brake, which is actually a fluid coupling with a housing restrained from rotating—similar to a water pump with no outlet.

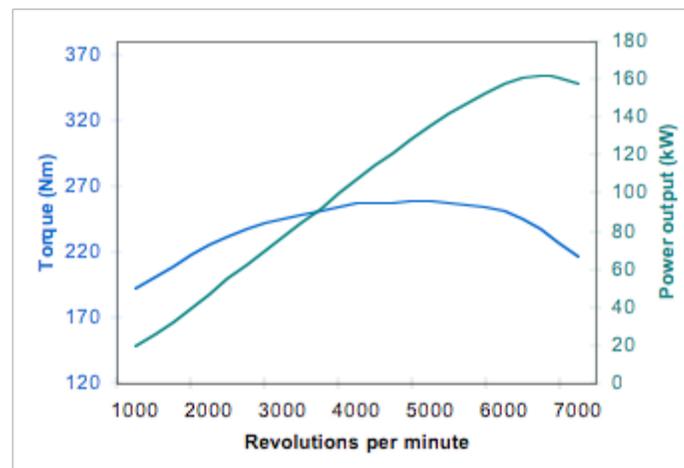
Compound Dynamometers

In most cases, motoring dynamometers are symmetrical; a 300 kW AC dynamometer can absorb 300 kW as well as motor at 300 kW. This is an uncommon requirement in engine testing and development. Sometimes, a more cost-effective solution is to attach a larger absorption dynamometer with a smaller motoring dynamometer; alternatively, a larger absorption dynamometer and a simple AC or DC motor may be used in a similar manner with the electric motor only providing motoring power when required and no absorption. The (cheaper) absorption dynamometer is sized for the maximum required absorption, whereas the motoring dynamometer is sized for motoring. A typical size ratio for common emission test cycles and most engine development is approximately 3:1. Torque measurement is somewhat complicated since there are two machines in tandem; an inline torque transducer is the preferred method of torque measurement in this case. An eddy-current or waterbrake dynamometer with electronic control combined with a variable frequency drive and AC induction motor is a commonly used configuration of this type. Disadvantages include requiring a second set of test cell services (electrical power and cooling), and a slightly more complicated control system. Attention must be paid to the transition between motoring and braking in terms of control stability.

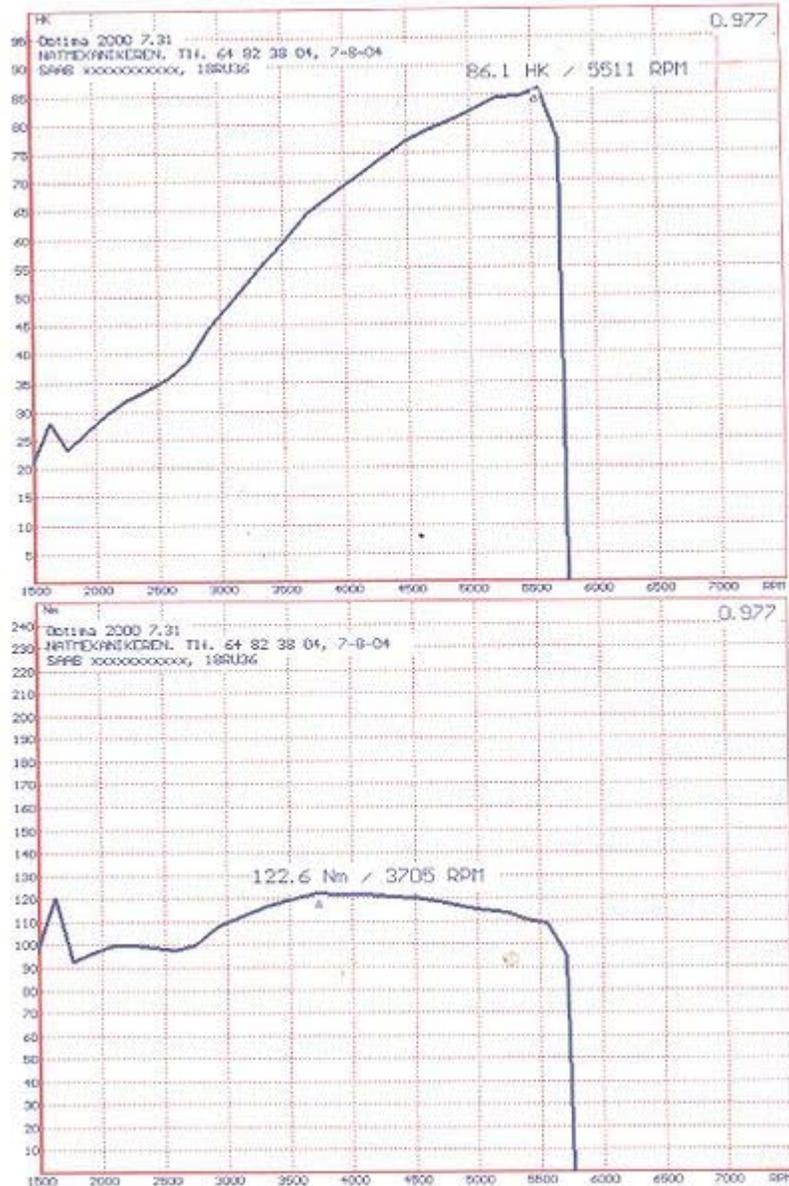
How dynamometers are used for engine testing

Dynamometers are useful in the development and refinement of modern day engine technology. The concept is to use a dyno to measure and compare power transfer at different points on a vehicle, thus allowing the engine or drivetrain to be modified to get more efficient power transfer. For example, if an engine dyno shows that a particular engine achieves 400 N·m (300 lbf·ft) of torque, and a chassis dynamo shows only 350 N·m (260 lbf·ft), one would know to look to the drivetrain for the major improvements. Dynamometers are typically very expensive pieces of equipment, reserved for certain fields that rely on them for a particular purpose.

Types of dynamometer systems



Dyno graph 1



Dyno graph 2

A **brake** dynamometer applies variable load on the Prime Mover (PM) and measures the PM's ability to move or hold the RPM as related to the "braking force" applied. It is usually connected to a computer that records applied braking torque and calculates engine power output based on information from a "load cell" or "strain gauge" and RPM (speed sensor).

An **inertia** dynamometer provides a fixed inertial mass load and calculates the power required to accelerate that fixed, known mass and uses a computer to record RPM and acc. rate to calculate torque. The engine is generally tested from somewhat above idle to its maximum RPM and the output is measured and plotted on a graph.

A **motoring** dynamometer provides the features of a brake dyne system, but in addition, can "power" (usually with an AC or DC motor) the Prime Mover (PM) and allow testing of very small power small outputs. Example, duplicating speeds and loads that are experienced when operating a vehicle traveling downhill or on/off throttle operations.

There are essentially 3 types of dynamometer test procedures

1. Steady state (only on brake dynamometers), where the engine is held at a specified RPM (or series of usually sequential RPMs) for a desired amount of time by the variable brake loading as provided by the PAU (power absorber unit)
2. Sweep test (on inertia or brake dynamometers), where the engine is tested under a load (inertia or brake loading), but allowed to "sweep" up in RPM in a continuous fashion, from a specified lower "starting" RPM to a specified "end" RPM
3. Transient test (usually on AC or DC dynamometers), where the engine power and speed are varied throughout the test cycle. Different test cycles are used in different jurisdictions. Chassis test cycles include the US light-duty UDDS, HWFET, US06, SC03, ECE, EUDC, and CD34. Engine test cycles include ETC, HDDTC, HDGTC, WHTC, WHSC, and ED12.

Types of Sweep Tests:

1. **Inertia sweep:** An inertia dyno system provides a fixed inertial mass flywheel and computes the power required to accelerate the flywheel (load) from the starting to the ending RPM. The actual rotational mass of the engine or engine and vehicle in the case of a chassis dyno is not known and the variability of even tire mass will skew power results. The inertia value of the flywheel is "fixed," so low power engines are under load for a much longer time and internal engine temperatures are usually too high by the end of the test, skewing optimal "dyno" tuning settings away from the outside world's optimal tuning settings. Conversely, high powered engines, commonly complete a common "4th gear sweep" test in less than 10 seconds, which is not a reliable load condition as compared to operation in the outside world. By not providing enough time under load, internal combustion chamber temps are unrealistically low and power readings, especially past the power peak, are skewed low.
1. **Loaded Sweep Tests** (brake dyno type) consist of 2 types:
 1. **Simple fixed Load Sweep Test:** A fixed load, of somewhat less than the engine's output, is applied during the test. The engine is allowed to accelerate from its starting RPM to its ending RPM, varying in its own acceleration rate, depending on power output at any particular RPM point. Power is calculated using $\text{torque} * \text{RPM} / 5252$ + the power required to accelerate the dyno and engine's / vehicle's rotating mass.
 2. **Controlled Acceleration Sweep Test:** Similar in basic usage as the above Simple fixed Load Sweep Test, but with the addition of active load control that targets a specific rate of acceleration. Commonly, 20fps/ps is used.

Controlled Acceleration Rate test is that the acc. rate used is controlled from low power to high power engines and over extension and contraction of "test duration" is avoided, providing more repeatable tests and tuning results.

In every Sweep Test, there is still the remaining issue of potential power reading error due to the variable engine / dyno / vehicle total rotating mass. Many modern computer controlled brake dyno systems are capable of deriving that "inertial mass" value to eliminate the error.

Interestingly, A "sweep test" will always be suspect, as many "sweep" users ignore the rotating mass factor and prefer to use a blanket "factor" on every test, on every engine or vehicle. Simple inertia dyne systems aren't capable of deriving "inertial mass" and are forced to use the same assumed inertial mass on every vehicle.

Using Steady State testing eliminates a Sweep Test rotating inertial mass error , as there is no acceleration during a Steady State test.

Transient Test Characteristics: Aggressive throttle movements, engine speed changes, and engine motoring are characteristics of most transient engine tests. The usual purpose of these tests are for vehicle emissions development and homologation. In some cases, the lower-cost eddy-current dynamometer is used to test one of the transient test cycles for early development and calibration. An eddy current dyne system offers fast load response, which allows rapid tracking of speed and load, but does not allow motoring. Since most required transient tests contain a significant amount of motoring operation, a transient test cycle with an eddy-current dyno will generate different emissions test results. Final adjustments are required to be done on a motoring-capable dyno.

Engine dynamometer



HORIBA engine dynamometer TITAN

An engine dynamometer measures power and torque directly from the engine's crankshaft (or flywheel), when the engine is removed from the vehicle. These dynos do not account for power losses in the drivetrain, such as the gearbox, transmission or differential etc.

Chassis dynamometer



Saab 96 on chassis dynamometer



AVL ROADSIM Light and medium duty vehicle chassis dynamometer for exhaust emission testing (Homologation) and other applications

A chassis dynamometer measures power delivered to the surface of the "drive roller" by the drive wheels. The vehicle is often parked on the roller or rollers, which the car then turns and the output is measured.

Modern roller type chassis dyne systems use the Salvisberg roller, which improved traction and repeatability over smooth or knurled drive rollers.

On a motorcycle, typical power loss at higher power levels, mostly through tire flex, is about 10% and gearbox chain and other power transferring parts are another 2% to 5%.

Other types of chassis dynamometers are available that eliminate the potential wheel slippage on old style drive rollers and attach directly to the vehicle's hubs for direct torque measurement from the axle. Hub mounted dynos include units made by Dynapack and Rototest.

Chassis dynos can be fixed or portable.

Modern chassis dynamometers can do much more than display RPM, horsepower, and torque. With modern electronics and quick reacting, low inertia dyne systems, it is now possible to tune to best power and the smoothest runs, in realtime.

In retail settings it is also common to "tune the air fuel ratio" , using a wideband oxygen sensor that is graphed along with RPM.

Some, dyne systems can also add vehicle diagnostic information to the dyno graph as well. This is done by gathering data directly from the vehicle using on-board diagnostics communication.

Emissions development and homologation dynamometer test systems often integrate emissions sampling, measurement, engine speed and load control, data acquisition, and safety monitoring into a complete test cell system. These test systems usually include complex emissions sampling equipment (such as constant volume samplers or raw exhaust gas sample preparation systems), and exhaust emissions analyzers. These analyzers are much more sensitive and much faster than a typical portable exhaust gas analyzer. Response times of well under one second are common and required by many transient test cycles.

Integration of the dynamometer control system along with automatic calibration tools for engine system calibration is often found in development test cell systems. In these test cell systems, the dynamometer load and engine speed are varied to many engine operating points, and selected engine management parameters are varied and the results recorded automatically. Later analysis of this data may then be used to generate engine calibration data used by the engine management software.

Because of frictional and mechanical losses in the various drivetrain components, the measured rear wheel brake horsepower is generally 15-20 percent less than the brake horsepower measured at the crankshaft or flywheel on an engine dynamometer. Other sources, after researching several different "engine" dyno software packages, found that the engine dyno user can integrally add "frictional loss" channel factors of +10% to +15% to the flywheel power, raising the claim that 20% to 25% or even more power is actually lost between the crankshaft at high power outputs.

Common misconceptions about dynos

Drag racing: 1/4 mile prediction based on dynamometer measured power

Horsepower figures are a strong predictor but do not guarantee a specific 0-60 mph, 1/4 mile elapsed time (ET) or 1/4 mile speed. An engine accelerating in a vehicle experiences different conditions than on a dyno. G forces and different temperatures as well as different modes of vibration in a vehicle can cause significant differences in power output.

Inexpensive "inertia dynamometers" commonly provide insufficient loading, and complete their "test" in less time than the real world 1/4 mile takes, causing inherent power value errors, due to unrealistic internal engine temperatures.

More sophisticated dyne systems are capable of "loaded testing," which can potentially recreate the same temperatures as on the drag strip.

In engineering units, the power figures used should be "True" or "Effective" horsepower scale.

Engine damage: Can dyno testing damage engines?

A brake dyno, in steady state mode only provides a load that is equal the amount of power that the engine is making at any specifically selected RPM point. If the engine makes 200 brake HP at 5000 RPM, the dynamometer's brake or power absorber will provide exactly 200 hp (150 kW) of load against it, keeping the RPM at 5000 RPM.

That's a realistic load that simulates a vehicle pulling a large trailer up a hill. It should be no problem on the dyno if there's no problem on the road.

Apprehension over dyno testing and engine damage has solid roots in fact. Old style dynamometers commonly used an inexpensive water brake type of power absorber. Load was increased or decreased by filling and draining water in the housing to change the amount of internal water volume to change the load, all the while draining and refilling the water to keep the water from boiling. It would sometimes take some time for the operator or computer to stabilize inflow and outflow rates. That extra time could pose a risk to engines.

Water brakes are still commonly used in applications where their small size and light weight are important and engine torque curves are relatively straight, as in large automotive and boats.

Engine testing may damage engines primarily due to insufficient instrumentation, insufficient safety monitoring systems, and insufficient cooling. An engine on a dyno does not receive air cooling due to engine speeds. Automotive engines are not typically designed for wide-open throttle operation for extended periods of time; internal components may overheat and fail.

History

Gaspard de Prony invented the de Prony brake in 1821. The de Prony brake (or Prony brake) is considered to be one of the earliest dynamometers.

Froude Hofmann of Worcester, UK, manufactures engine and vehicle dynamometers. They credit William Froude with the invention of the hydraulic dynamometer in 1877

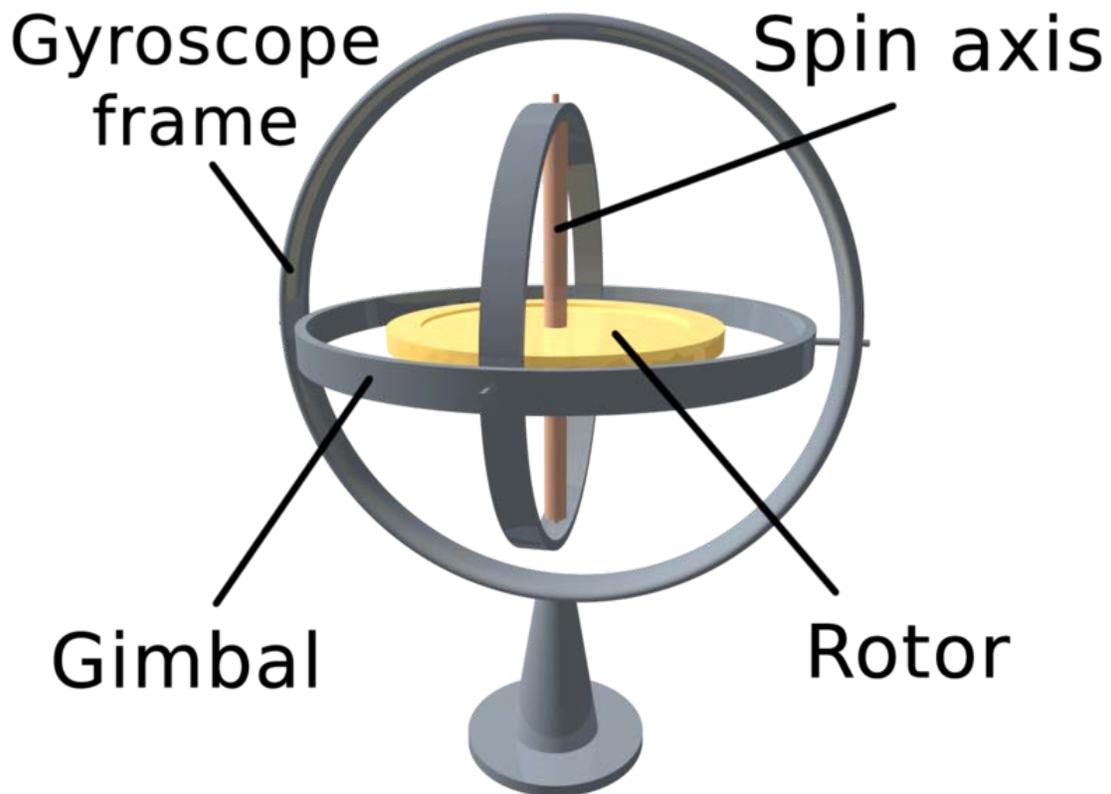
and say that the first commercial dynamometers were produced in 1881 by their predecessor company, Heenan & Froude.

In 1928, the German company "*Carl Schenck Eisengießerei & Waagenfabrik*" built the first vehicle dynamometers for brake tests with the basic design of the today's vehicle test stands.

The eddy current dynamometer was invented by Martin and Anthony Winther in about 1931. At that time, DC Motor/generator dynamometers had been in use for many years. A company founded by the Winthers, Dynamatic Corporation, manufactured dynamometers in Kenosha, Wisconsin until 2002. Dynamatic was part of Eaton Corporation from 1946 to 1995. In 2002, Dyne Systems of Jackson, Wisconsin acquired the Dynamatic dynamometer product line. Starting in 1938, Heenan & Froude manufactured eddy current dynamometers for many years under license from Dynamatic and Eaton.

Chapter 5

Gyroscope



A gyroscope

A **gyroscope** is a device for measuring or maintaining orientation, based on the principles of conservation of angular momentum. A mechanical gyroscope is essentially a spinning wheel or disk whose axle is free to take any orientation. This orientation changes much less in response to a given external torque than it would without the large angular momentum associated with the gyroscope's high rate of spin. Since external torque is

minimized by mounting the device in gimbals, its orientation remains nearly fixed, regardless of any motion of the platform on which it is mounted.

Gyroscopes based on other operating principles also exist, such as the electronic, microchip-packaged MEMS gyroscope devices found in consumer electronic devices, solid state ring lasers, fibre optic gyroscopes and the extremely sensitive quantum gyroscope.

Applications of gyroscopes include navigation (INS) when magnetic compasses do not work (as in the Hubble telescope) or are not precise enough (as in ICBMs) or for the stabilization of flying vehicles like radio-controlled helicopters or UAVs. Due to their high precision, gyroscopes are also used to maintain direction in tunnel mining.

Description and diagram

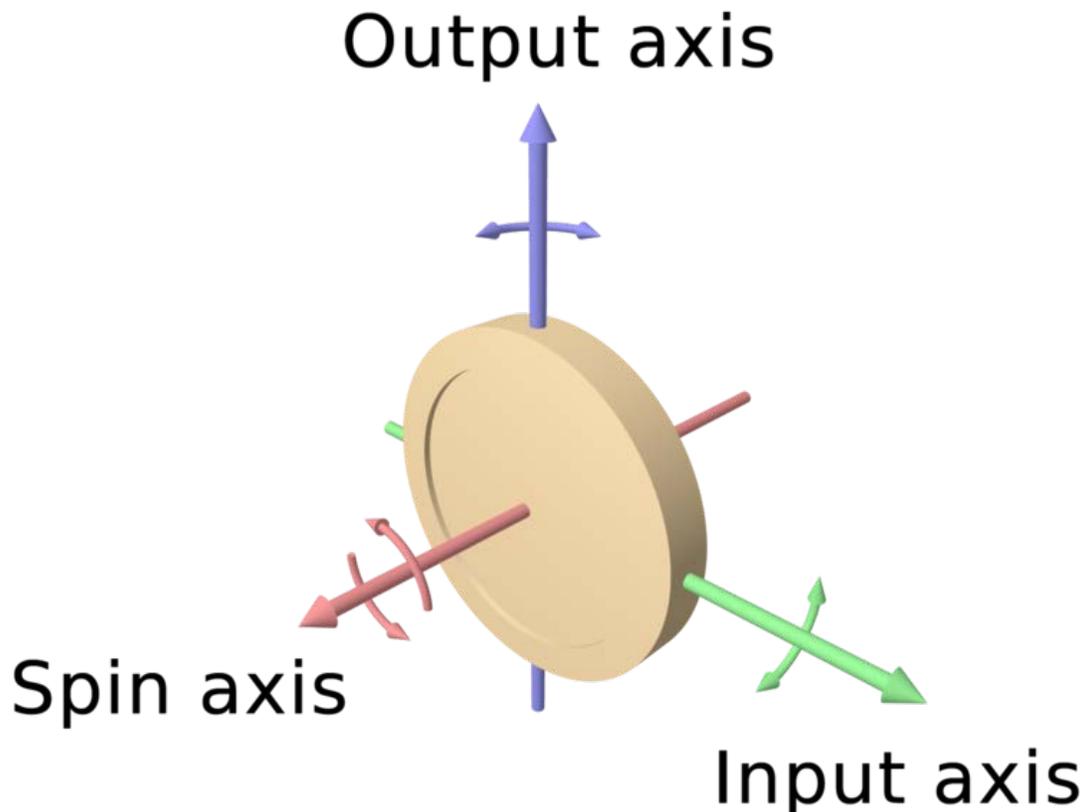


Diagram of a gyro wheel. Reaction arrows about the output axis (blue) correspond to forces applied about the input axis (green), and vice versa.

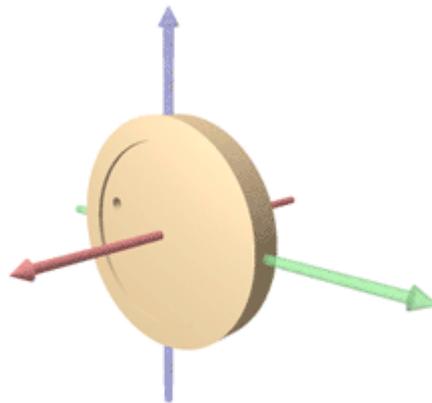
Within mechanical systems or devices, a conventional *gyroscope* is a mechanism comprising a rotor journalled to spin about one axis, the journals of the rotor being mounted in an inner gimbal or ring, the inner gimbal is journalled for oscillation in an outer gimbal which is journalled in another gimbal for a total of three gimbals.

The **outer gimbal** or ring which is the gyroscope frame is mounted so as to pivot about an axis in its own plane determined by the support. This outer gimbal possesses one degree of rotational freedom and its axis possesses none. The next **inner gimbal** is mounted in the gyroscope frame (outer gimbal) so as to pivot about an axis in its own plane that is always perpendicular to the pivotal axis of the gyroscope frame (outer gimbal). This inner gimbal has two degrees of rotational freedom. Similarly, next **innermost gimbal** is attached to the inner gimbal which has three degrees of rotational freedom and its axis possesses two.

The axle of the spinning wheel defines the spin axis. The rotor is journaled to spin about an axis which is always perpendicular to the axis of the innermost gimbal. So, the rotor possesses four degrees of rotational freedom and its axis possesses three. The wheel responds to a force applied about the input axis by a reaction force about the output axis.

The behaviour of a gyroscope can be most easily appreciated by consideration of the front wheel of a bicycle. If the wheel is leaned away from the vertical so that the top of the wheel moves to the left, the forward rim of the wheel also turns to the left. In other words, rotation on one axis of the turning wheel produces rotation of the third axis.

A **gyroscope flywheel** will roll or resist about the output axis depending upon whether the output gimbals are of a free- or fixed- configuration. Examples of some free-output-gimbal devices would be the attitude reference gyroscopes used to sense or measure the pitch, roll and yaw attitude angles in a spacecraft or aircraft.



Gyro wheel in action

The centre of gravity of the rotor can be in a fixed position. The rotor simultaneously spins about one axis and is capable of oscillating about the two other axes, and thus, except for its inherent resistance due to rotor spin, it is free to turn in any direction about the fixed point. Some gyroscopes have mechanical equivalents substituted for one or more of the elements, e.g., the spinning rotor may be suspended in a fluid, instead of being pivotally mounted in gimbals. A control moment gyroscope (CMG) is an example

of a fixed-output-gimbal device that is used on spacecraft to hold or maintain a desired attitude angle or pointing direction using the gyroscopic resistance force.

In some special cases, the outer gimbal (or its equivalent) may be omitted so that the rotor has only two degrees of freedom. In other cases, the centre of gravity of the rotor may be offset from the axis of oscillation and thus the centre of gravity of the rotor and the centre of suspension of the rotor may not coincide.

History



Gyroscope invented by Léon Foucault in 1852. Replica built by Dumoulin-Froment for the Exposition universelle in 1867. National Conservatory of Arts and Crafts museum, Paris.

The earliest known gyroscope-like instrument was made by German Johann Bohnenberger, who first wrote about it in 1817. At first he called it the "Machine".

Bohnenberger's machine was based on a rotating massive sphere. In 1832, American Walter R. Johnson developed a similar device that was based on a rotating disk. The French mathematician Pierre-Simon Laplace, working at the École Polytechnique in Paris, recommended the machine for use as a teaching aid, and thus it came to the attention of Léon Foucault. In 1852, Foucault used it in an experiment involving the rotation of the Earth. It was Foucault who gave the device its modern name, in an experiment to see the Earth's rotation (Greek *gyros*, circle or rotation), which was visible in the 8 to 10 minutes before friction slowed the spinning rotor.

In the 1860s, the advent of electric motors made it possible for a gyroscope to spin indefinitely; this led to the first prototype gyrocompasses. The first functional marine gyrocompass was patented in 1907 by German inventor Hermann Anschütz-Kaempfe. The American Elmer Sperry followed with his own design later that year, and other nations soon realized the military importance of the invention—in an age in which naval prowess was the most significant measure of military power—and created their own gyroscope industries. The Sperry Gyroscope Company quickly expanded to provide aircraft and naval stabilizers as well, and other gyroscope developers followed suit.

In 1917, the Chandler Company of Indianapolis, Indiana, created the "Chandler gyroscope", a toy gyroscope with a pull string and pedestal. Chandler continued to produce the toy until the company was purchased by TEDCO inc. in 1982. The Chandler toy is still produced by TEDCO today.

In the first several decades of the 20th century, other inventors attempted (unsuccessfully) to use gyroscopes as the basis for early black box navigational systems by creating a stable platform from which accurate acceleration measurements could be performed (in order to bypass the need for star sightings to calculate position). Similar principles were later employed in the development of inertial guidance systems for ballistic missiles.

During World War Two, the gyroscope became the prime component for aircraft and anti-aircraft gun sights.

Properties



A gyroscope in operation with freedom in all three axes. The rotor will maintain its spin axis direction regardless of the orientation of the outer frame.

A gyroscope exhibits a number of behaviours including precession and nutation. Gyroscopes can be used to construct gyrocompasses which complement or replace magnetic compasses (in ships, aircraft and spacecraft, vehicles in general), to assist in stability (Hubble Space Telescope, bicycles, motorcycles, and ships) or be used as part of an inertial guidance system. Gyroscopic effects are used in tops, boomerangs, yo-yos, and Powerballs. Many other rotating devices, such as flywheels, behave gyroscopically although the gyroscopic effect is not being used.

The fundamental equation describing the behavior of the gyroscope is:

$$\boldsymbol{\tau} = \frac{d\mathbf{L}}{dt} = \frac{d(I\boldsymbol{\omega})}{dt} = I\boldsymbol{\alpha}$$

where the vectors $\boldsymbol{\tau}$ and \mathbf{L} are, respectively, the torque on the gyroscope and its angular momentum, the scalar I is its moment of inertia, the vector $\boldsymbol{\omega}$ is its angular velocity, and the vector $\boldsymbol{\alpha}$ is its angular acceleration.

It follows from this that a torque $\boldsymbol{\tau}$ applied perpendicular to the axis of rotation, and therefore perpendicular to \mathbf{L} , results in a rotation about an axis perpendicular to both $\boldsymbol{\tau}$ and \mathbf{L} . This motion is called *precession*. The angular velocity of precession $\boldsymbol{\Omega}_p$ is given by the cross product:

$$\boldsymbol{\tau} = \boldsymbol{\Omega}_p \times \mathbf{L}.$$



Precession on a gyroscope

Precession can be demonstrated by placing a spinning gyroscope with its axis horizontal and supported loosely (frictionless toward precession) at one end. Instead of falling, as might be expected, the gyroscope appears to defy gravity by remaining with its axis horizontal, when the other end of the axis is left unsupported and the free end of the axis slowly describes a circle in a horizontal plane, the resulting precession turning. This effect is explained by the above equations. The torque on the gyroscope is supplied by a couple of forces: gravity acting downwards on the device's centre of mass, and an equal force acting upwards to support one end of the device. The rotation resulting from this torque is not downwards, as might be intuitively expected, causing the device to fall, but perpendicular to both the gravitational torque (horizontal and perpendicular to the axis of rotation) and the axis of rotation (horizontal and outwards from the point of support), i.e. about a vertical axis, causing the device to rotate slowly about the supporting point.

Under a constant torque of magnitude τ , the gyroscope's speed of precession Ω_p is inversely proportional to L , the magnitude of its angular momentum:

$$\tau = \Omega_p L \sin \theta,$$

where θ is the angle between the vectors Ω_p and \mathbf{L} . Thus if the gyroscope's spin slows down (for example, due to friction), its angular momentum decreases and so the rate of precession increases. This continues until the device is unable to rotate fast enough to support its own weight, when it stops precessing and falls off its support, mostly because friction against precession cause another precession that goes to cause the fall.

By convention, these three vectors, torque, spin, and precession, are all oriented with respect to each other according to the right-hand rule.

To easily ascertain the direction of gyro effect, simply remember that a rolling wheel tends, when it leans to the side, to turn in the direction of the lean.

Variations

Gyrostat

A **gyrostat** is a variant of the gyroscope. It consists of a massive flywheel concealed in a solid casing. Its behaviour on a table, or with various modes of suspension or support, serves to illustrate the curious reversal of the ordinary laws of static equilibrium due to the gyrostatic behaviour of the interior invisible flywheel when rotated rapidly. The first gyrostat was designed by Lord Kelvin to illustrate the more complicated state of motion of a spinning body when free to wander about on a horizontal plane, like a top spun on the pavement, or a hoop or bicycle on the road.

MEMS

A MEMS gyroscope takes the idea of the Foucault pendulum and uses a vibrating element, known as a MEMS (Micro Electro-Mechanical System). The MEMS-based gyro was initially made practical and producible by Systron Donner Inertial (SDI). Today, SDI is a large manufacturer of MEMS gyroscopes.

FOG

A fiber optic gyroscope (FOG) is a gyroscope that uses the interference of light to detect mechanical rotation. The sensor is a coil of as much as 5 km of optical fiber. The development of low loss single mode optical fiber in the early 1970s for the telecommunications industry enabled the development of Sagnac effect fiber optic gyros.

VSG or CVG

A vibrating structure gyroscope (VSG), also called a **coriolis vibratory gyroscope** (CVG), uses a resonator made of different metallic alloys. It takes a position between the low accuracy, low cost MEMS gyroscope and the higher accuracy and higher cost fiber optic gyroscope (FOG). Accuracy parameters are increased by using low intrinsic damping materials, resonator vacuumization, and digital electronics to reduce temperature dependent drift and instability of control signals.

High-Q Wine-Glass Resonators for precise sensors like HRG or CRG are based on Bryan's "wave inertia effect". They are made from high-purity quartz glass or from single-crystalline sapphire.

DTG

A dynamically tuned gyroscope (DTG) is a rotor suspended by a universal joint with flexure pivots. The flexure spring stiffness is independent of spin rate. However, the dynamic inertia (from the gyroscopic reaction effect) from the gimbal provides negative spring stiffness proportional to the square of the spin speed (Howe and Savet, 1964; Lawrence, 1998). Therefore, at a particular speed, called the tuning speed, the two moments cancel each other, freeing the rotor from torque, a necessary condition for an ideal gyroscope.

London moment

A London moment gyroscope relies on the quantum-mechanical phenomenon whereby a spinning superconductor generates a magnetic field whose axis lines up exactly with the spin axis of the gyroscopic rotor. A magnetometer determines the orientation of the generated field, which is interpolated to determine the axis of rotation. Gyroscopes of this type can be extremely accurate and stable, for example those used in the Gravity Probe B experiment measured changes in gyroscope spin axis orientation to better than 0.5 milliarcseconds (1.4×10^{-7} degrees) over a one-year period. This is equivalent to an angular separation the width of a human hair viewed from 32 kilometers (20 miles) away.

The GP-B gyro consists of a nearly-perfect spherical rotating mass made of fused quartz which provides a dielectric support for a thin layer of niobium superconducting material. To eliminate friction found in conventional mechanical bearings, the rotor assembly is suspended by six electromagnets that form a magnetic bearing. After the initial spin-up by a jet of helium brings the rotor to 4,000 RPM, the polished gyroscope housing is evacuated to a ultra-high vacuum to further reduce drag on the rotor. Provided the suspension electronics remain powered, the extreme rotational symmetry, lack of friction, and low drag will allow the angular momentum of the rotor to keep it spinning for about 15,000 years.

A sensitive DC SQUID magnetometer able to discriminate changes as small as one quantum, or about 2×10^{-15} Wb, is used to monitor the gyroscope. A precesses, or tilt, in the orientation of the rotor causes the London moment magnetic field to shift relative to the housing. The moving field passes through a superconducting pickup loop fixed to the housing, inducing a small electric current. The current produces a voltage across a shunt resistance, which is resolved to spherical coordinates by a microprocessor. The system is designed to minimize Lorentz torque on the rotor.

Modern uses

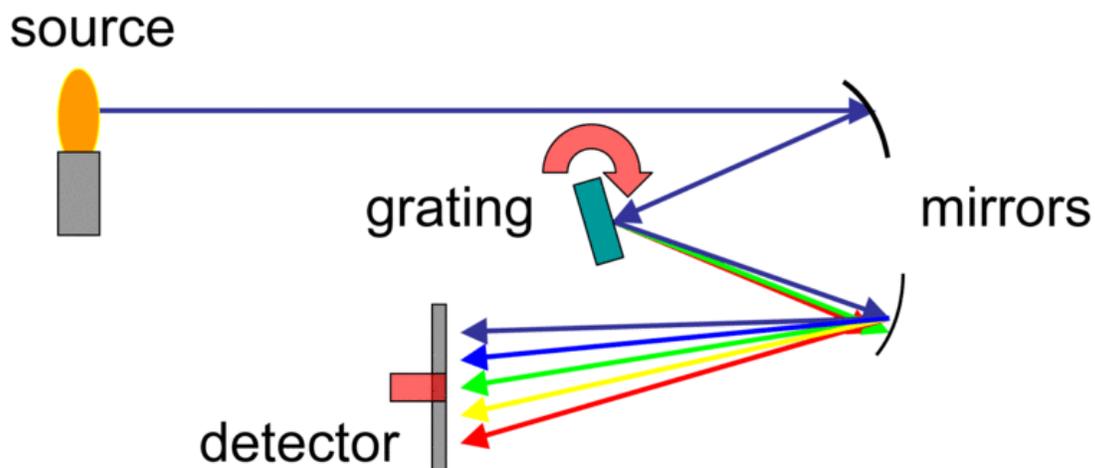
In addition to being used in compasses, aircraft, computer pointing devices, etc., gyroscopes have been introduced into consumer electronics. Since the gyroscope allows the calculation of orientation and rotation, designers have incorporated them into modern technology. The integration of the gyroscope has allowed for more accurate recognition of movement within a 3D space than the previous lone accelerometer within a number of smartphones. Scott Steinberg, known for his critiques on newly released technology, says

that the new addition of the gyroscope in the iPhone 4 may "completely redefine the way we interact with downloadable apps".

Nintendo has integrated a gyroscope into the Wii console's Wii Remote controller by an additional piece of hardware called "Wii MotionPlus".

Chapter 6

Spectrometer



Grating spectrometer schematic

A **spectrometer** (**spectrophotometer**, **spectrograph** or **spectroscope**) is an instrument used to measure properties of light over a specific portion of the electromagnetic spectrum, typically used in spectroscopic analysis to identify materials. The variable measured is most often the light's intensity but could also, for instance, be the polarization state. The independent variable is usually the wavelength of the light or a unit directly proportional to the photon energy, such as wavenumber or electron volts, which has a reciprocal relationship to wavelength. A spectrometer is used in spectroscopy for producing spectral lines and measuring their wavelengths and intensities.

Spectrometer is a term that is applied to instruments that operate over a very wide range of wavelengths, from gamma rays and X-rays into the far infrared. If the instrument is designed to measure the spectrum in absolute units rather than relative units, then it is typically called a spectrophotometer. The majority of spectrophotometers are used in spectral regions near the visible spectrum.

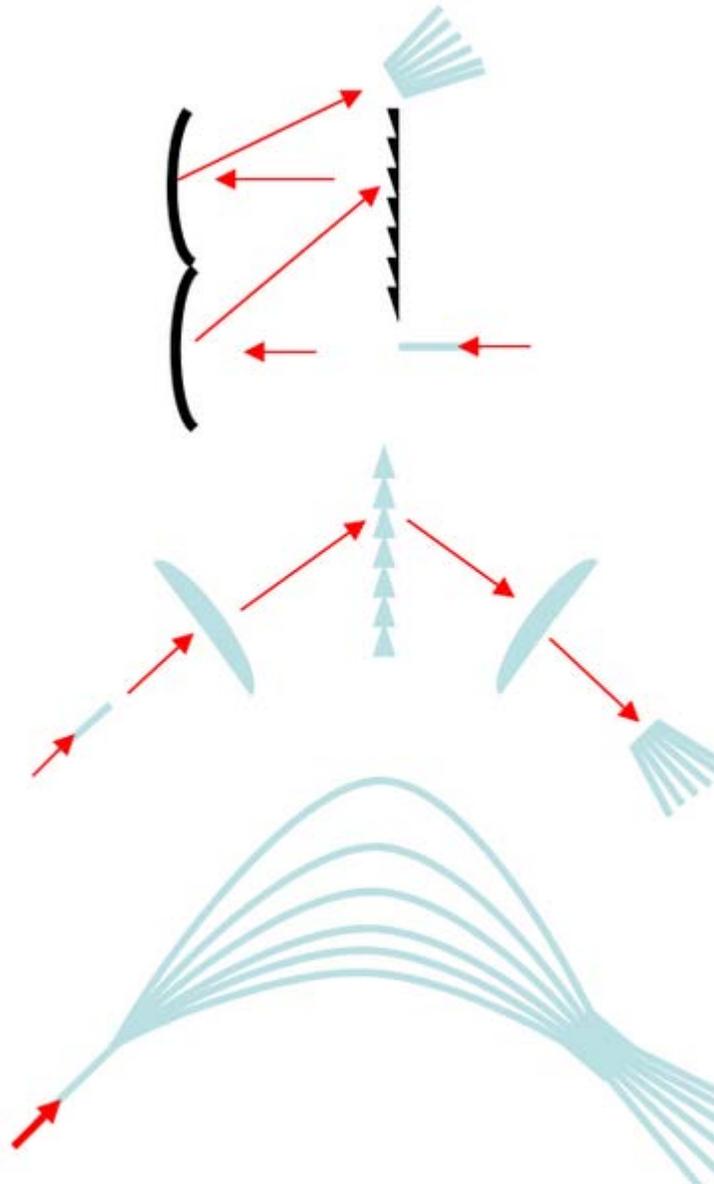
In general, any particular instrument will operate over a small portion of this total range because of the different techniques used to measure different portions of the spectrum. Below optical frequencies (that is, at microwave and radio frequencies), the spectrum analyzer is a closely related electronic device.

Spectroscopes

Spectroscope



Other names	Spectrograph
Related items	Mass spectrograph



Comparison of different diffraction based spectrometers: Reflection optics, refraction optics, fiber optics

Spectroscopes are often used in astronomy and some branches of chemistry. Early spectroscopes were simply prisms with graduations marking wavelengths of light. Modern spectroscopes generally use a diffraction grating, a movable slit, and some kind of photodetector, all automated and controlled by a computer. The spectroscope was invented by Joseph von Fraunhofer.

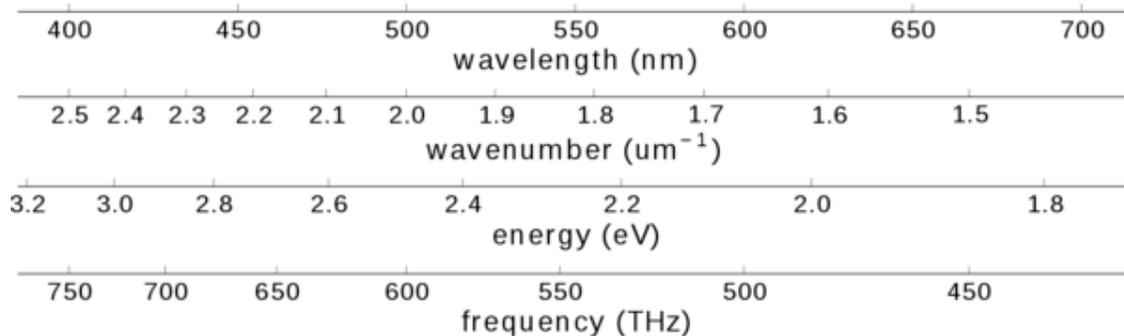
When a material is heated to incandescence it emits light that is characteristic of the atomic makeup of the material. Particular light frequencies give rise to sharply defined bands on the scale which can be thought of as fingerprints. For example, the element sodium has a very characteristic double yellow band known as the Sodium D-lines at

588.9950 and 589.5924 nanometers, the color of which will be familiar to anyone who has seen a low pressure sodium vapor lamp.

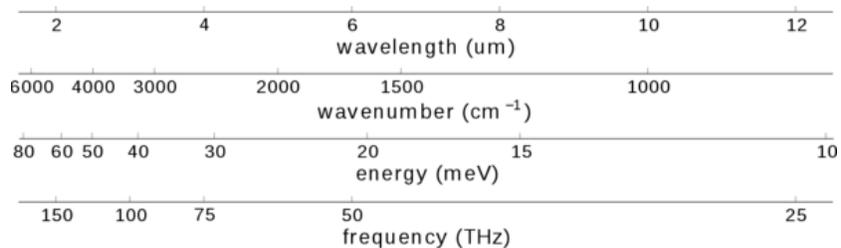
In the original spectroscope design in the early 19th century, light entered a slit and a collimating lens transformed the light into a thin beam of parallel rays. The light then passed through a prism (in hand-held spectroscopes, usually an Amici prism) that refracted the beam into a spectrum because different wavelengths were refracted different amounts due to dispersion. This image was then viewed through a tube with a scale that was transposed upon the spectral image, enabling its direct measurement.

With the development of photographic film, the more accurate spectrograph was created. It was based on the same principle as the spectroscope, but it had a camera in place of the viewing tube. In recent years the electronic circuits built around the photomultiplier tube have replaced the camera, allowing real-time spectrographic analysis with far greater accuracy. Arrays of photosensors are also used in place of film in spectrographic systems. Such spectral analysis, or spectroscopy, has become an important scientific tool for analyzing the composition of unknown material and for studying astronomical phenomena and testing astronomical theories.

In modern spectrographs in the UV, visible, and near-IR spectral ranges, the spectrum is generally given in the form of photon number per unit wavelength (nm or μm), wavenumber (μm^{-1} , cm^{-1}), frequency (THz), or energy (eV), with the units indicated by the abscissa. In the mid- to far-IR, spectra are typically expressed in units of Watts per unit wavelength (μm) or wavenumber (cm^{-1}). In many cases, the spectrum is displayed with the units left implied (such as "digital counts" per spectral channel).



A comparison of the four abscissa types typically used for visible spectrometers.



A comparison of the four abscissa types typically used for infrared spectrometers.

Spectrographs



A very simple spectroscope based on a prism

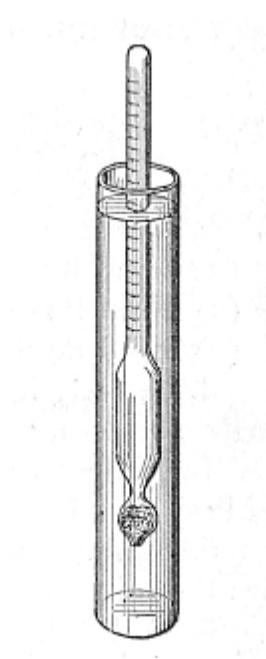
A **spectrograph** is an instrument that separates an incoming wave into a frequency spectrum. There are several kinds of machines referred to as *spectrographs*, depending on the precise nature of the waves. The first spectrographs used photographic paper as the detector. The star spectral classification and discovery of the main sequence, Hubble's law and the Hubble sequence were all made with spectrographs that used photographic paper. The plant pigment phytochrome was discovered using a spectrograph that used living plants as the detector. More recent spectrographs use electronic detectors, such as CCDs which can be used for both visible and UV light. The exact choice of detector depends on the wavelengths of light to be recorded.

An echelle spectrograph uses two diffraction gratings, rotated 90 degrees with respect to each other and placed close to one another. Therefore an entrance point and not a slit is used and a 2d CCD-chip records the spectrum. Usually one would guess to retrieve a spectrum on the diagonal, but when both gratings have a wide spacing and one is blazed so that only the first order is visible and the other is blazed that a lot of higher orders are visible, one gets a very fine spectrum nicely folded onto a small common CCD-chip. The small chip also means that the collimating optics need not to be optimized for coma or astigmatism, but the spherical aberration can be set to zero.

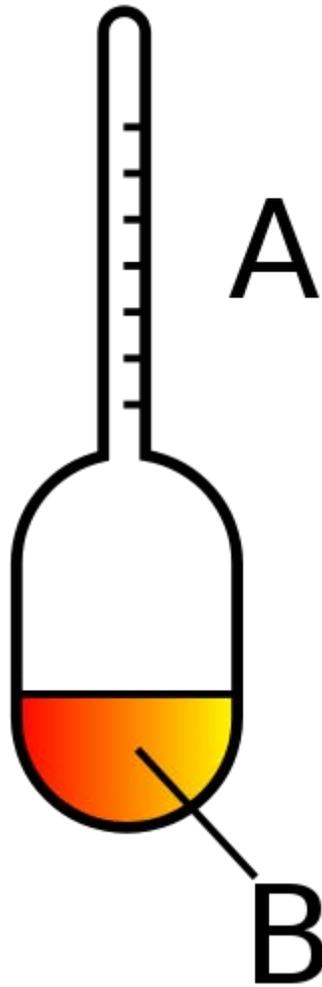
A spectrograph is sometimes called polychromator, as an analogy to monochromator.

Chapter 7

Hydrometer



Hydrometer from Practical Physics



Scheme of an Aerometer

A **hydrometer** is an instrument used to measure the specific gravity (or relative density) of liquids; that is, the ratio of the density of the liquid to the density of water.

A hydrometer is usually made of glass and consists of a cylindrical stem and a bulb weighted with mercury or lead shot to make it float upright. The liquid to be tested is poured into a tall container, often a graduated cylinder, and the hydrometer is gently lowered into the liquid until it floats freely. The point at which the surface of the liquid touches the stem of the hydrometer is noted. Hydrometers usually contain a scale inside the stem, so that the specific gravity can be read directly. A variety of scales exist, and are used depending on the context.

Hydrometers may be calibrated for different uses, such as a lactometer for measuring the density (creaminess) of milk, a saccharometer for measuring the density of sugar in a liquid, or an alcoholometer for measuring higher levels of alcohol in spirits.

Principle

Operation of the hydrometer is based on Archimedes' principle that a solid suspended in a fluid will be buoyed up by a force equal to the weight of the fluid displaced. Thus, the lower the density of the substance, the farther the hydrometer will sink.

History

An early description of a hydrometer appears in a letter from Synesius of Cyrene to the Greek scholar Hypatia of Alexandria. In Synesius' fifteenth letter, he requests Hypatia to make a hydrometer for him. Hypatia is given credit for inventing the hydrometer (or hydroscope) sometime in the late 4th century or early 5th century.

The instrument in question is a cylindrical tube, which has the shape of a flute and is about the same size. It has notches in a perpendicular line, by means of which we are able to test the weight of the waters. A cone forms a lid at one of the extremities, closely fitted to the tube. The cone and the tube have one base only. This is called the baryllium. Whenever you place the tube in water, it remains erect. You can then count the notches at your ease, and in this way ascertain the weight of the water.

It was used by Abū Rayhān al-Bīrūnī in the 11th century and described by Al-Khazini in the 12th century. It later appeared again in the work of Jacques Alexandre César Charles in the 18th century.

Ranges

In low-density liquids such as kerosene, gasoline, and alcohol, the hydrometer will sink deeper, and in high-density liquids such as brine, milk, and acids it will not sink so far. In fact, it is usual to have two separate instruments, one for heavy liquids, on which the mark 1.000 for water is near the top of the stem, and one for light liquids, on which the mark 1.000 is near the bottom. In many industries a set of hydrometers is used — covering specific gravity ranges of 1.0–0.95, 0.95–0.9 etc. — to provide more precise measurements.

Scales

Modern hydrometers usually measure specific gravity but different scales were (and sometimes still are) used in certain industries. Examples include:

- API gravity, universally used worldwide by the petroleum industry.
- Baumé scale, formerly used in industrial chemistry and pharmacology
- Brix scale, primarily used in fruit juice, wine making and the sugar industry
- Oechsle scale, used for measuring the density of grape must
- Plato scale, primarily used in brewing
- Twaddell scale, formerly used in the bleaching and dyeing industries

Specialized hydrometers

Specialized hydrometers are frequently named for their use: a lactometer, for example, is a hydrometer designed especially for use with dairy products.

Lactometer

A lactometer (or galactometer) is a hydrometer used to test milk. The specific gravity of milk does not give a conclusive indication of its composition since milk contains a variety of substances that are either heavier or lighter than water. Additional tests for fat content are necessary to determine overall composition. The instrument is graduated into a hundred parts. Milk is poured in and allowed to stand until the cream has formed, then the depth of the cream deposit in degrees determines the quality of the milk.

Alcoholometer

An alcoholometer is a hydrometer which is used for determining the alcoholic strength of liquids. It is also known as a proof and trailie hydrometer. It only measures the density of the fluid. Certain assumptions are made to estimate the amount of alcohol present in the fluid. Alcoholometers have scales marked with volume percents of "potential alcohol", based on a pre-calculated specific gravity. A higher "potential alcohol" reading on this scale is caused by a greater specific gravity, assumed to be caused by the introduction of dissolved sugars. A reading is taken before and after fermentation and approximate alcohol content is determined by subtracting the post fermentation reading from the pre-fermentation reading.

Saccharometer

A saccharometer is a hydrometer used for determining the amount of sugar in a solution. It is used primarily by winemakers and brewers, and it can also be used in making sorbets and ice-creams. The first brewers' saccharometer was constructed by John Richardson in 1784.

It consists of a large weighted glass bulb with a thin stem rising from the top with calibrated markings. The sugar level can be determined by reading the value where the surface of the liquid crosses the scale. It works by the principle of buoyancy. A solution with a higher sugar content is denser, causing the bulb to float higher. Less sugar results in a lower density and a lower floating bulb.

Thermohydrometer

A thermohydrometer is a hydrometer that has a thermometer enclosed in the float section. For measuring the density of petroleum products, like fuel oils, the specimen is usually heated in a temperature jacket with a thermometer placed behind it since density is dependent on temperature. Light oils are placed in cooling jackets, typically at 15°C.

Very light oils with many volatile components are measured in a variable volume container using a floating piston sampling device to minimize light end losses.

As a battery test it measures the temperature compensated specific gravity and electrolyte temperature.

Urinometer

A urinometer is a medical hydrometer designed for urinalysis. As urine's specific gravity is dictated by its ratio of solutes (wastes) to water, a urinometer makes it possible to quickly assess a patient's overall level of hydration.

Barkometer

A barkometer is calibrated to test the strength of tanning liquors used in tanning leather.

Battery hydrometer

The state of charge of a lead-acid battery can be estimated from the density of the sulphuric acid solution used as electrolyte. A hydrometer calibrated to read specific gravity relative to water at 60 degrees Fahrenheit is a standard tool for servicing automobile batteries. Tables are used to correct the reading to the standard temperature.

Antifreeze tester

Another automotive use of hydrometers is testing the quality of the antifreeze solution used for engine cooling. The degree of freeze protection can be related to the density (and so concentration) of the antifreeze; different types of antifreeze have different relations between measured density and freezing point.

Acidometer

Sometimes spelled acidimeter, an acidometer is a hydrometer used to measure the specific gravity of an acid.

Use in soil analysis

A hydrometer analysis is the process by which fine-grained soils, silts and clays, are graded. Hydrometer analysis is performed if the grain sizes are too small for sieve analysis. The basis for this test is Stoke's Law for falling spheres in a viscous fluid in which the terminal velocity of fall depends on the grain diameter and the densities of the grain in suspension and of the fluid. The grain diameter thus can be calculated from a knowledge of the distance and time of fall. The hydrometer also determines the specific gravity (or density) of the suspension, and this enables the percentage of particles of a certain equivalent particle diameter to be calculated.

Chapter 8

Tachometer



Left figure shows a tachometer that can show up to 6000 and 7000 RPM

A **tachometer** (also called a **revolution-counter**, "Tach", **rev-counter**, or **RPM gauge**) is an instrument that measures the rotation speed of a shaft or disk, as in a motor or other machine. The device usually displays the revolutions per minute (RPM) on a calibrated analogue dial, but digital displays are increasingly common. The term comes from Greek *Ταχος*, *tachos*, "speed", and *metron*, "to measure".

History

The first mechanical tachometers were based on measuring the centrifugal force, similar to the operation of a centrifugal governor. The inventor is assumed to be the German engineer Dietrich Uhlhorn; he used it for measuring the speed of machines in 1817. Since 1840, it has been used to measure the speed of locomotives.

In automobiles, trucks, tractors and aircraft



Cessna 172's G1000 tachometer (1,060 RPM) and engine hours (1736.7 hours)

Tachometers or rev counters on automobiles, aircraft, and other vehicles show the rate of rotation of the engine's crankshaft, and typically have markings indicating a safe range of

rotation speeds. This can assist the driver in selecting appropriate throttle and gear settings for the driving conditions. Prolonged use at high speeds may cause inadequate lubrication, overheating (exceeding capability of the cooling system), exceeding speed capability of sub-parts of the engine (for example spring retracted valves) thus causing excessive wear or permanent damage or failure of engines. This is more applicable to manual transmissions than to automatics. On analogue tachometers, speeds above maximum safe operating speed are typically indicated by an area of the gauge marked in red, giving rise to the expression of "redlining" an engine — revving the engine up to the maximum safe limit. The red zone is superfluous on most modern cars, since their engines typically have a rev limiter which electronically limits engine speed to prevent damage. Diesel engines with traditional mechanical injector systems have an integral governor which prevents over-speeding the engine, so the tachometers in vehicles and machinery fitted with such engines sometimes lack a redline.

In vehicles such as tractors and trucks, the tachometer often has other markings, usually a green arc showing the speed range in which the engine produces maximum torque, which is of prime interest to operators of such vehicles. Tractors fitted with a power take off (PTO) system have tachometers showing the engine speed needed to rotate the PTO at the standardised speed required by most PTO-driven implements. In many countries, tractors are required to have a speedometer for use on a road. To save fitting a second dial, the vehicle's tachometer is often marked with a second scale in units of speed. This scale is only accurate in a certain gear, but since many tractors only have one gear that is practical for use on-road, this is sufficient. Tractors with multiple 'road gears' often have tachometers with more than one speed scale. Aircraft tachometers have a green arc showing the engine's designed cruising speed range.

In older vehicles, the tachometer is driven by the RMS voltage waves from the low tension (LT) side of the ignition coil, while on others (and nearly all diesel engines, which have no ignition system) engine speed is determined by the frequency from the alternator tachometer output. This is a special circuit inside the alternator to convert from rectified sine wave to square wave, and the electrical potential difference is directly proportional to engine speed. Tachometers driven by a rotating cable from a drive unit fitted to the engine (usually on the camshaft) also exist - usually on simple diesel-engined machinery with basic or no electrical systems. On recent EMS found on modern vehicles, the signal for the tachometer is usually generated from an ECU which derives the information from either the crankshaft or camshaft speed sensor.

Hours meters

When used in stationary engines or vehicles where an odometer would not give an accurate reading of the vehicle's use (such as in aircraft, boats or tractors), tachometers frequently incorporate a display showing the total number of hours the engine has run. Service intervals are given and measured in hours. Generally, hours meters are accurate only at one specific engine speed — an hours meter calibrated for, say, 'Hours At 2000 RPM' will only advance one hour per hour if the engine is run at 2000 RPM. If the engine is run below this speed, hours will accumulate more slowly, and if the engine is run

above the meter will gain hours more quickly. This discrepancy does not detract from the accuracy of service intervals, for an engine running at slow speeds may gain hours more slowly, but will also be put under less mechanical stress and will not require servicing work as frequently as an engine used generally at high speeds.

Traffic Engineering

Tachometers are used to estimate traffic speed and volume (flow). A vehicle is equipped with the sensor and conducts "tach runs" which record the traffic data. These data are a substitute or complement to loop detector data. To get statistically significant results usually requires a fairly high number of runs, and bias is introduced by the time of day, day of week, and the season. However, because of the expense, spacing (a lower density of loop detectors diminishes data accuracy), and relatively low reliability of loop detectors (often 30% or more are out of service at any give time), tach runs remain a common practice.

In trains and light rail vehicles

Speed sensing devices, termed variously "wheel impulse generators" (WIG), speed probes, or tachometers are used extensively in rail vehicles. Common types include opto-isolator slotted disk sensors and Hall effect sensors.

Hall effect sensors typically use a rotating target attached to a wheel, gearbox or motor. This target may contain magnets, or it may be a toothed wheel. The teeth on the wheel vary the flux density of a magnet inside the sensor head. The probe is mounted with its head a precise distance from the target wheel and detects the teeth or magnets passing its face. One problem with this system is that the necessary air gap between the target wheel and the sensor allows ferrous dust from the vehicle's underframe to build up on the probe or target, inhibiting its function.

Opto-isolator sensors are completely encased to prevent ingress from the outside environment. The only exposed parts are a sealed plug connector and a drive fork, which is attached to a slotted disk internally through a bearing and seal. The slotted disk is typically sandwiched between two circuit boards containing a photo-diode, photo-transistor, amplifier, and filtering circuits which produce a square wave pulse train output customized to the customers voltage and pulses per revolution requirements. These types of sensors typically provide 2 to 8 independent channels of output that can be sampled by other systems in the vehicle such as automatic train control systems and propulsion/braking controllers.

The opto devices, mounted around the circumference of the disk, provide signals that are phase-shifted relative to one another and thus allow the vehicle computer to determine the direction of rotation of the wheel. This is a legal requirement in Switzerland to prevent *rollback* when starting from standstill. Strictly, such devices are not tachometers since they do not provide a direct reading of the rotational speed of the disk. The speed has to be derived externally by counting the number of pulses in a time period. It is

difficult to prove conclusively that the vehicle is stationary, other than by waiting a certain time to ensure that no further pulses occur. This is one reason why there is often a time delay between the train stopping, as perceived by a passenger, and the doors being released. Slotted-disk devices are typical sensors used in odometer systems for rail vehicles, such as are required for train protection systems — notably the European Train Control System.

A weakness of systems that rely on wheel rotation for tachometry and odometry is that the train wheels and the rails are very smooth and the friction between them is low, leading to high error rates if the wheels slip or slide. To compensate for this, secondary odometry inputs employ Doppler radar units beneath the train to measure speed independently.

As well as speed sensing, these probes are often used to calculate distance traveled by multiplying wheel rotations by wheel circumference.

They can also be used to automatically calibrate wheel diameter by comparing the number of rotations of each axle against a master wheel that has been measured manually. Since all wheels travel the same distance, the diameter of each wheel is proportional to its number of rotations compared to the master wheel. This calibration must be done while coasting at a fixed speed to eliminate the possibility of wheel slip/slide introducing errors into the calculation. Automatic calibration of this type is used to generate more accurate traction and braking signals, and to improve wheel slip detection.

In analogue audio recording

In analogue audio recording, a tachometer is a device that measures the speed of audiotape as it passes across the head. On most audio tape recorders the tachometer (or simply "tach") is a relatively large spindle near the ERP head stack, isolated from the feed and take-up spindles by tension idlers.

On many recorders the tachometer spindle is connected by an axle to a rotating magnet that induces a changing magnetic field upon a Hall effect transistor. Other systems connect the spindle to a stroboscope, which alternates light and dark upon a photodiode.

The tape recorder's drive electronics use signals from the tachometer to ensure that the tape is played at the proper speed. The signal is compared to a reference signal (either a quartz crystal or alternating current from the mains). The comparison of the two frequencies drives the speed of the tape transport. When the tach signal and the reference signal match, the tape transport is said to be "at speed." (To this day on film sets, the director calls "Roll sound!" and the sound man replies "Sound speed!" This is a vestige of the days when recording devices required several seconds to reach a regulated speed.)

Having perfectly regulated tape speed is important because the human ear is very sensitive to changes in pitch, particularly sudden ones, and without a self-regulating

system to control the speed of tape across the head the pitch could drift several percent. This effect is called a wow-and-flutter, and a modern, tachometer-regulated cassette deck has a wow-and-flutter of 0.07%.

Tachometers are acceptable for high-fidelity sound playback, but not for recording in synchronization with a movie camera. For such purposes, special recorders that record pilot tone must be used.

Tachometer signals can be used to synchronize several tape machines together, but only if in addition to the tach signal, a directional signal is transmitted, to tell slave machines in which direction the master is moving.

Chapter 9

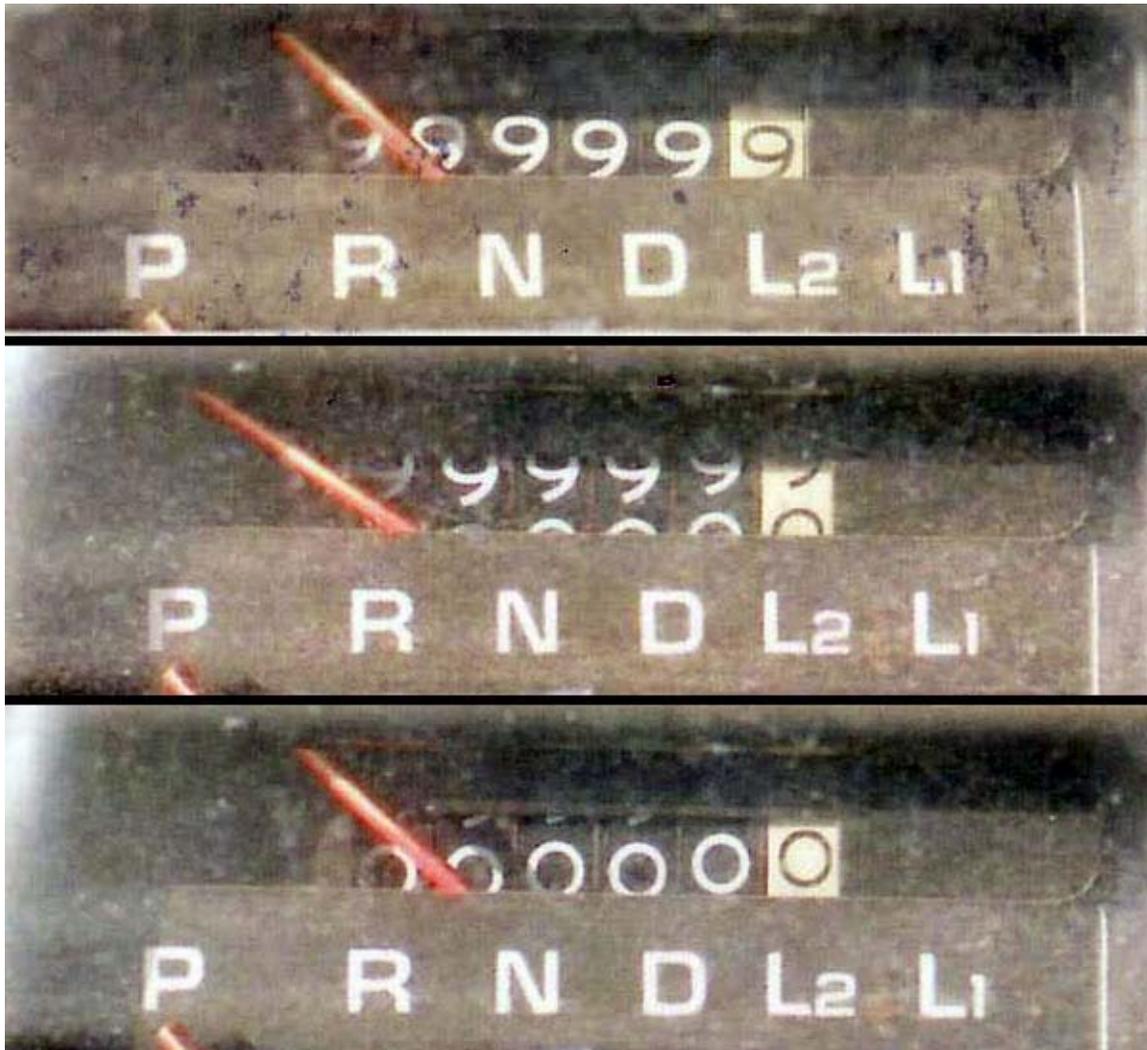
Odometer



A mechanical odometer with trip meter below.

An **odometer** (**mileometer**, **milometer**) indicates distance travelled by a car or other vehicle. The device may be electronic, mechanical, or a combination of the two. The word derives from the Greek words *hodós*, meaning "path" or gateway and "métron", "measure".

Description



Odometer rollover.

In the early cars a top reading of 99,999 was enough. With improvements, modern vehicles need an extra digit. At the top reading, an odometer restarts from zero (odometer rollover).

Most modern cars include a **trip meter (trip odometer)**. Unlike the odometer, a trip meter is reset at any point in a journey, making it possible to record the distance travelled in any particular journey or part of a journey. It was traditionally a purely mechanical device but, in most modern vehicles, it is now electronic. Luxury vehicles often have multiple trip meters. Most trip meters will show a maximum value of 999.9. The trip meter may be used to record the distance travelled on each tank of fuel, making it very easy to accurately track the energy efficiency of the vehicle; another common use is resetting it to zero at each instruction in a sequence of driving directions, to be sure when one has arrived at the next turn.

History



A Smiths speedometer from the 1920s showing odometer and trip meter.



An electronic odometer with digital display

Western world

Possibly the first evidence for the use of an odometer can be found in the works of Pliny (NH 6. 61-62) and Strabo (11.8.9). Both authors list the distances of routes travelled by Alexander the Great (r. 336-323 BC) as measured by his bematists Diognetus and Baeton. However, the high precision of the bematists's measurements rather indicates the use of a mechanical device. For example, the section between the cities Hecatompylos and Alexandria Areion, which later became a part of the silk road, was given by Alexander's bematists as 529 English miles long, that is with a deviation of 0.4% from the actual distance (531 English miles). From the nine surviving bematists' measurements in Pliny's *Naturalis Historia* eight show a deviation of less than 5% from the actual distance, three of them being within 1%. Since these minor discrepancies can be adequately explained by slight changes in the tracks of roads during the last 2300 years, the overall accuracy of the measurements implies that the bematists already must have used a sophisticated device for measuring distances, although there is no direct mentioning of such a device.

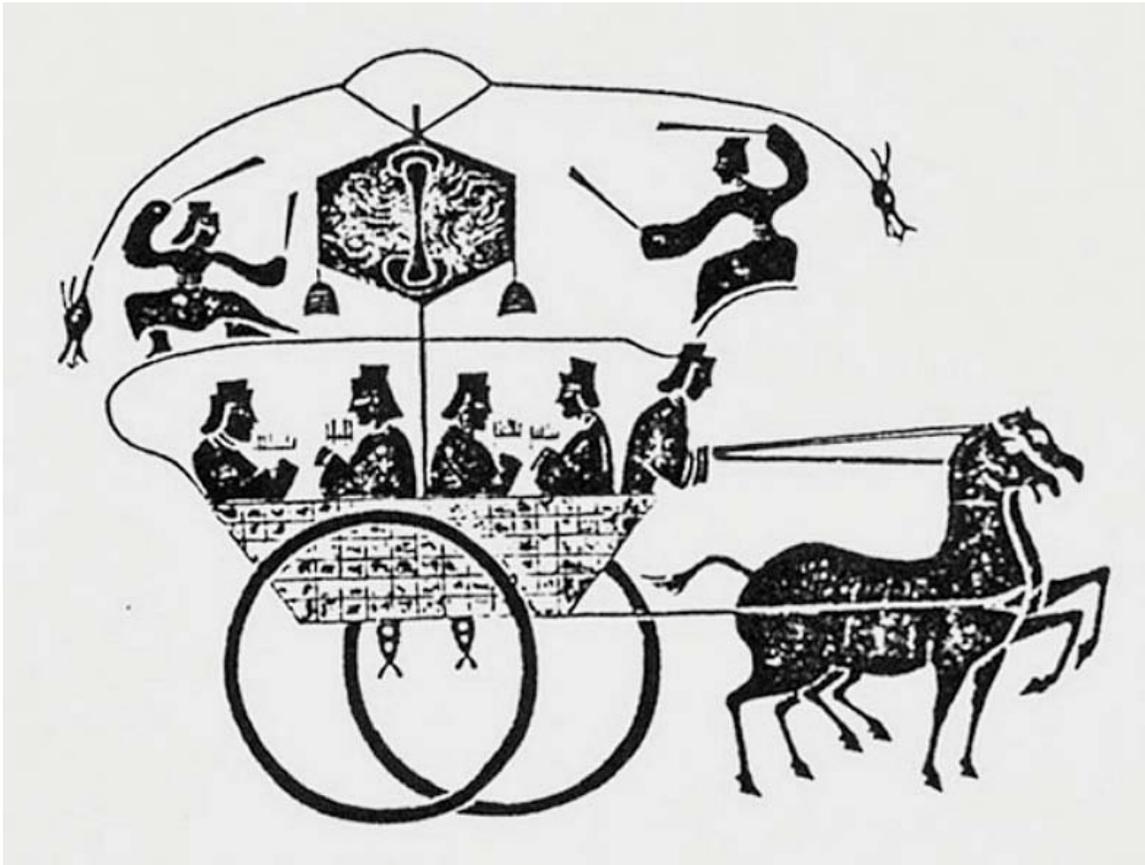
An odometer for measuring distance was first described by Vitruvius around 27 and 23 BC. The actual invention *may* have been by Archimedes of Syracuse during the First

Punic War. Hero of Alexandria describes a similar device in chapter 34 of his *Dioptra*. The machine was also used in the time of Roman Emperor Commodus (c. 192 AD), although after this point in time there seems to be a gap between its use in Roman times and that of the 15th century in Western Europe.

The odometer of Vitruvius was based on chariot wheels of 4 feet (1.2 m) diameter turning 400 times in one Roman mile (about 1400 m). For each revolution a pin on the axle engaged a 400 tooth cogwheel thus turning it one complete revolution per mile. This engaged another gear with holes along the circumference, where pebbles (*calculus*) were located, that were to drop one by one into a box. The distance travelled would thus be given simply by counting the number of pebbles. Whether this instrument was ever built at the time is disputed. Leonardo da Vinci tried to build it according to the description but failed. Later, Ben Franklin invented his own version. Benjamin Franklin invented a simple odometer when he was going on trips in carriages. He wanted to know how far he was going, and the speed he was travelling.

The odometer as used in modern systems, where a separate gear controls each digit, was invented in 1847 by William Clayton with help from Orson Pratt and Appleton Harmon. Clayton, a Mormon pioneer, developed the odometer (dubbed the "roadometer") to keep track of wheel revolutions on the pioneer wagons. The odometer had at least two gears, including one which turned every quarter-mile and one which turned every ten miles.

China



A Han Dynasty stone rubbing of a horse-drawn odometer cart.

The odometer was also later invented in ancient China, possibly by the profuse inventor and early scientist Zhang Heng (78–139 AD) of the Han Dynasty (202 BC–220 AD). Zhang Heng is often accredited with the invention of the first odometer device in China, an achievement alongside earlier contemporaries Archimedes and Heron of Alexandria from the Hellenized West. By the 3rd century (during the Three Kingdoms Period), the Chinese had termed the device as the 'jì lǐ gǔ chē' (記里鼓車), or 'li-recording drum carriage' (Note: the modern measurement of li = 500 m/1640 ft). Chinese texts of the 3rd century tell of the mechanical carriage's functions, and as one li is traversed, a mechanical-driven wooden figure strikes a drum, and when ten li is traversed, another wooden figure would strike a gong or a bell with its mechanical-operated arm.

Despite its association with Zhang Heng or even the later Ma Jun (c. 200–265), there is evidence to suggest that the invention of the odometer was a gradual process in Han Dynasty China that centered around the *huang men* court people (i.e. eunuchs, palace officials, attendants and familiars, actors, acrobats, etc.) that would follow the musical procession of the royal 'drum-chariot'. The historian Joseph Needham asserts that it is no surprise this social group would have been responsible for such a device, since there is already other evidence of their craftsmanship with mechanical toys to delight the emperor

and the court. There is speculation that some time in the 1st century BC (during the Western Han Dynasty), the beating of drums and gongs were mechanically-driven by working automatically off the rotation of the road-wheels. This might have actually been the design of one Loxia Hong (c. 110 BC), yet by 125 AD the mechanical odometer carriage in China was already known (depicted in a mural of the Xiao Tang Shan Tomb).

The odometer was used also in subsequent periods of Chinese history. In the historical text of the *Jin Shu* (635 AD), the oldest part of the compiled text, the book known as the *Cui Bao* (c. 300 AD), recorded the use of the odometer, providing description (and interestingly enough attributing it to the Western Han era, from 202 BC–9 AD). The passage in the *Jin Shu* expanded upon this, explaining that it took a similar form to the mechanical device of the South Pointing Chariot invented by Ma Jun. As recorded in the *Song Shi* of the Song Dynasty (960-1279 AD), the odometer and South Pointing Chariot were combined into one wheeled device by engineers of the 9th century, 11th century, and 12th century (refer to South Pointing Chariot). The *Sun Tzu Suan Ching* (Master Sun's Mathematical Manual), dated from the 3rd century to 5th century, presented a mathematical problem for students involving the odometer. It involved a given distance between two cities, the small distance needed for one rotation of the carriage's wheel, and the posed question of how many rotations the wheels would have in all if the carriage was to travel between point A and B.

In full description

The historical text of the *Song Shi* (1345 AD), recording the people and events of the Chinese Song Dynasty (960–1279), also mentioned the odometer used in that period. However, unlike written sources of earlier periods, it provided a much more thoroughly detailed description of the device that harkens back to its ancient form (Wade-Giles spelling):

The odometer. [The mile-measuring carriage] is painted red, with pictures of flowers and birds on the four sides, and constructed in two storeys, handsomely adorned with carvings. At the completion of every li, the wooden figure of a man in the lower storey strikes a drum; at the completion of every ten li, the wooden figure in the upper storey strikes a bell. The carriage-pole ends in a phoenix-head, and the carriage is drawn by four horses. The escort was formerly of 18 men, but in the 4th year of the Yung-Hsi reign-period (987 AD) the emperor Thai Tsung increased it to 30. In the 5th year of the Thien-Sheng reign-period (1027 AD) the Chief Chamberlain Lu Tao-lung presented specifications for the construction of odometers as follows:

What follows is a long dissertation made by the Chief Chamberlain Lu Daolong on the ranging measurements and sizes of wheels and gears, along with a concluding description at the end of how the device ultimately functions:

The vehicle should have a single pole and two wheels. On the body are two storeys, each containing a carved wooden figure holding a drumstick. The road-wheels are each 6 ft in diameter, and 18 ft in circumference, one revolution covering 3 paces. According to

ancient standards the pace was equal to 6 ft and 300 paces to a li; but now the li is reckoned as 360 paces of 5 ft each.

The vehicle wheel (li lun) is attached to the left road-wheel; it has a diameter of 1.38 ft with a circumference of 4.14 ft, and has 18 cogs (chhih) 2.3 inches apart. There is also a lower horizontal wheel (hsia phing lun), of diameter 4.14 ft and circumference 12.42 ft, with 54 cogs, the same distance apart as those on the vertical wheel (2.3 inches). (This engages with the former.)

Upon a vertical shaft turning with this wheel, there is fixed a bronze "turning-like-the-wind wheel" (hsuan feng lun) which has (only) 3 cogs, the distance between these being 1.2 inches. (This turns the following one.) In the middle is a horizontal wheel, 4 ft in diameter, and 12 ft circumference, with 100 cogs, the distance between these cogs being the same as on the "turning-like-the-wind wheel" (1.2 inches).

Next, there is fixed (on the same shaft) a small horizontal wheel (hsiao phing lun) 3.3 inches in diameter and 1 ft in circumference, having 10 cogs 1.5 inches apart. (Engaging with this) there is an upper horizontal wheel (shang phing lun) having a diameter of 3.3 ft and a circumference of 10 ft, with 100 cogs, the same distance apart as those of the small horizontal wheel (1.5 inches).

When the middle horizontal wheel has made 1 revolution, the carriage will have gone 1 li and the wooden figure in the lower story will strike the drum. When the upper horizontal wheel has made 1 revolution, the carriage will have gone 10 li and the figure in the upper storey will strike the bell. The number of wheels used, great and small, is 8 inches in all, with a total of 285 teeth. Thus the motion is transmitted as if by the links of a chain, the "dog-teeth" mutually engaging with each other, so that by due revolution everything comes back to its original starting point (ti hsiang kou so, chhuan ya hsiang chih, chou erh fu shih).

Modern history

In modern times, Andre Sleeswyk was able to make a working model of an odometer using gears similar to the Antikythera mechanism as opposed to the traditional cogwheel.

Clocking and legality

A common form of fraud is to tamper with the reading on an odometer; this is often referred to as clocking. This is done to make a car appear to have been driven less than it really has been, and thus increase its apparent market value. Many new cars sold today use digital odometers that store the mileage in the vehicle's engine control module making it difficult (but not impossible) to manipulate the mileage electronically. With mechanical odometers, the speedometer can be removed from the car dash board and the digits wound back, or the drive cable can be disconnected and connected to another odometer/speedometer pair while on the road. Modern odometers now add mileage

driven in reverse to the total as if driven forward, to accurately reflect the true total wear and tear on the vehicle (older vehicles could be driven in reverse to subtract mileage).

The resale value of a vehicle is often strongly influenced by the number of miles or kilometres a passenger vehicle has on the odometer, yet odometers are inherently insecure because they are under the control of their owners. Many jurisdictions have chosen to enact laws which penalize people who are found to commit odometer fraud. In the US (and many other countries), vehicle mechanics are also required to keep records of the odometer any time a vehicle is serviced. Companies such as Carfax then use this data to help potential car buyers detect whether odometer rollback has occurred.

GPS used as odometer



A Garmin etrex H GPS receiver, showing an odometer, trip odometer as well as speed related information

Recently, exercise enthusiasts have observed that an advanced Global Positioning System receiver (GPSr) with an odometer mode serves as a very accurate pedometer for outdoor activities. While not truly counting steps (no pendulum is involved) an advanced GPS odometer can accurately reveal the distance traveled to within 1/100 of a mile (depending on the model, perhaps 1/1000 of a mile). 1/1000 of a mile is approximately the distance of a single pace or 2 steps (1.609 m). Precise metric odometers have a precision of 1/100 or 1/1000 km, 10 or 1 metre(s) respectively.

A GPS with odometer mode is also an excellent and inexpensive means to verify proper operation of both the speedometer and odometer mounted in a vehicle.

Odometer tax

This would be a road vehicle tax collected per distance unit of travel. This may become increasingly important with the increasing presence of gas burning vehicles & very fuel efficient electric models.