PROBLEM 1.1

SOLUTION

This problem is open-ended and has no unique solution. We suggest that the instructor use this Problem as the basis for an in-class or small group discussion.

Example:
Home heating thermostat (see photo):

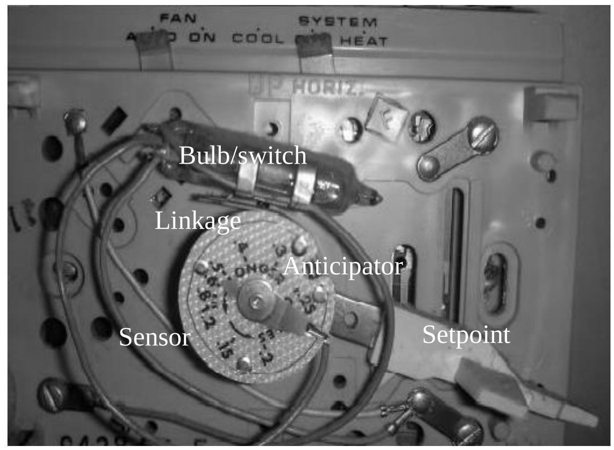


Photo of the insides of a generic analog thermostat

Analog type:
Sensor - bimetallic thermometer (round part in center of photo) that lengthens so as to unroll with temperature rise;
Signal conditioning –linkage/motion of sensor that mechanically moves a mercury bulb (seen as the elongated tube) as sensor temperature changes;
Controller- mercury bulb contact switch that turns furnace on/off based on (1) the setpoint temperature (position of long handle) and (2) position of bulb: changing the setpoint rotates one end of bulb so it is more or is less horizontal, whereas changing sensor temperature rotates bulb so it is more or it is less horizontal. The net effect is to open or close the contact switch;
Output display – room thermometer on outside of thermostat to show actual local temperature (not shown).
Other signal conditioning components: **anticipator** – adjustable mechanical thermal device that triggers the off signal before the setpoint temperature is reached (anticipating residual heating from furnace): essentially this provides an adjustable temperature offset, it is located in the center of the round part in the figure). The wires in photo connect to the furnace and to power.

Digital type: **sensor** – thermistor (a type of resistor whose resistance is temperature based). It replaces analog coil in photo; **signal conditioning** – circuit that determines temperature by measuring the current flowing through the thermistor and sends a proportional voltage signal to controller (replaces linkage in photo); **output display** – usually a separate LCD thermometer; **controller** – PID device, a proportional integral device controller that calculates an error value, which is simply the difference between the sensed and setpoint temperatures. The device attempts to minimize the error by turning the furnace on/off. It replaces the bulb in the photo.

PROBLEM 1.2

FIND: Identify measurement stages for each device.

SOLUTION

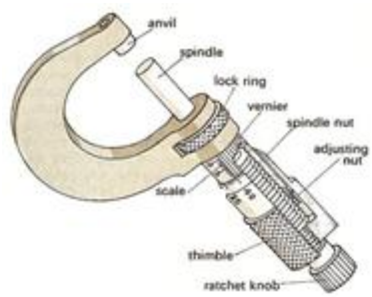
a) Microphone/amplifier/speaker system

Sensor: microphone diaphragm
Transducer: microphone coil/magnet. Diaphragm displacement relative to coil generates a small voltage proportional to diaphragm displacement
Signal conditioning: amplifier. It increases the level of the microphone signal sufficient to drive the output stage
Output: loud speaker. Its voice coil responds to the varying applied voltage output of the amplifier and this moves the speaker cone (opposite of the microphone).

b) thermostat

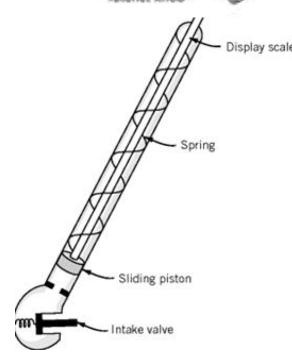
Sensor/transducer: bimetallic thermometer. Temperature changes cause the metal to expand or contract. Coil absorbs prevailing temperature, material expands/contracts changing the thermal energy into a mechanical displacement (transducer)
Output: displacement of thermometer tip
Controller: mercury contact switch (open: furnace off; closed: furnace on)

c) hand-held micrometer



sensor: space between anvil and spindle
transducer: displacement of spindle via the spindle thimble
Output: vernier scale

d) tire pressure gage (pencil-style)



Sensor: chamber behind the valve and piston equalizes pressure with tire
Transducer: piston
Signal conditioning: piston translates chamber pressure relative to atmospheric pressure into displacement
Output: readout scale

PROBLEM 1.3

FIND: Discuss interference in the test of Example 1.1 (Figure 1.5)

SOLUTION :

In the example shown by Figure 1.5, tests were run on different days on which the local barometric pressure had changed. Between any two days of different barometric pressure, the boiling point measured would be different – this offset is due to the interference effect of the pressure.

Consider a test run over several days coincident with the motion of a major weather front through the area. Clearly, this would impose a trend on the dataset. For example, the measured boiling point may be seen as increasing from day to day.

By running tests over random days separated by a sufficient period of days, so as not to allow any one atmospheric front to impose a trend on the data, the effects of atmospheric pressure can be broken up into noise. The measured boiling point might then be high one test but then low on the next, in effect, making it look like random data scatter, i.e. noise.

PROBLEM 1.4

FIND: Examples of continuous and discrete variables

SOLUTION :

Continuous: These are variables that have possible values that could encompass any (an infinite number) value within a range. In engineering, we usually associate these as variables that vary with time or space.

A value taken from a continuous line graph

Outdoor air temperature

The length of a kitchen appliance cord (think about the different appliances and the range of possible lengths. The length of any one appliance is typically anywhere between 30 and 150 cm)

Discrete: These are variables that have possible values that are distinct and separate, such as 0, 1, 2.

Number of phone (or messages) calls you received in a day.

Number of heads found in a group of coin tosses

Score of a basketball (soccer, baseball, …) game (think about the possible outcomes of these games. The scores are integers and a direct count)

COMMENT

Most times we can distinguish between the two by deciding if the variable is the result of a measurement or an exact count. Also in most cases, digital displays are discrete; analog displays are continuous.

PROBLEM 1.5

FIND: How accurate is a thermometer? Estimate uncertainty?

SOLUTION

As a check for accuracy:

First, look at the temperature readout. Does the indicated temperature make sense? This is a sanity check. If it fails here, no need to proceed.

The next check would be either: (1) place the thermometer into a condition where the temperature is known (i.e., a known setpoint), or (2) compare it to another temperature indicator of known accuracy at different temperatures that span the desired range of use.

> Either of these methods is a form of calibration. An easy temperature test is to use the ice point, which is at 0 ^{o}C. This is created by filling an insulated beaker full of ice cubes with pure water, just enough to fill the interstitial volume and allowed the mixture to equalize). In fact, the freezing/melting point of pure solids is used to establish the accuracy of temperature sensors as these temperatures are repeatable and known. Another easy setpoint is to use the boiling water temperature.

The ice point test will indicate any offset in the thermometer. This offset is a measure of the systematic uncertainty. You can correct for the offset but the correction is limited by how well you know the correction. Also, the correction may change with temperature. So doing several (at least two) set point calibrations will help.

If you compare against another thermometer, the systematic uncertainty will also be dependent on the accuracy of the comparison thermometer. Yes, there is a measure of vagueness involved; that is the calibration uncertainty. But you at least gain a measurable amount of confidence in the unknown thermometer reading.

A check for random uncertainty is to place the thermometer into a known temperature environment and read its temperature. Do this repeatedly over a period of time. A statistical analysis of the average and deviation in temperature is a measure of random uncertainty. However: This test will indicate a measure of the repeatability of the thermometer, but it will also indicate how well the known temperature was held constant. The two effects are coupled in the random uncertainty.

PROBLEM 1.6

FIND: How does resolution of a scale affect uncertainty?

SOLUTION

The resolution of a scale is defined by the least significant increment or division on the output display. Resolution affects a user's ability to resolve the output display of an instrument or measuring system, and thereby can introduce error, in this case a resolution error. Thus, there is a source of uncertainty associated with this error. The uncertainty value is the range of possible resolution error.

So, if the indicator has finite resolution, then the measurement has at least some uncertainty based on how well you can resolve a reading. This will show as a type of random uncertainty. Example: take a photograph of a scale reading and show it to twenty people. Record the readings made by the twenty people. The scatter in the data of that sample of twenty will be indicative of the random uncertainty due to resolution error.

The resolution would not contribute to systematic error, as systematic error is a fixed offset.

PROBLEM 1.7

KNOWN: A bulb thermometer is used to measure outside temperature.

FIND: Extraneous variables that might influence thermometer output.

SOLUTION

A thermometer's indicated temperature will be influenced by the temperature of solid objects to which it is in contact, and radiation exchange with bodies at different temperatures (including the sky or sun, buildings, people and ground) within its line of sight. Hence, location should be carefully selected and even randomized. We know that a bulb thermometer does not respond quickly to temperature changes, so that a sufficient period of time needs to be allowed for the instrument to adjust to new temperatures. By replication of the measurement, effects due to instrument hysteresis and instrument and procedural repeatability can be randomized.

Because of limited resolution in such an instrument, different competent temperature observers might record different indicated temperatures even if the instrument output were fixed. Either observers should be randomized or, if not, the test replicated. It is interesting to note that such a randomization will bring about a predictable scatter in recorded data of about ½ the resolution of the instrument scale.

PROBLEM 1.8

KNOWN: Input voltage, (E_i) and Load (τ_L) can be controlled and varied.

Efficiency (η), Winding temperature (T_w), and Current (I) are measured.

FIND: Specify the dependent, independent in the test and suggest any extraneous variables.

SOLUTION

The measured variables are the dependent variables in the test and they depend on the independent variables of input voltage and load. Several influencing extraneous variables include: ambient temperature (T_a) and relative humidity R; Line voltage fluctuations (e); and each of the individual measuring instruments (m_i). The variation of the independent variables should be performed separately maintaining one independent variable fixed while the other is systematically varied over the test range. A random test procedure for the independent variable will randomize the effects of T_a, R and e. Replication methods using different test instruments would be one way to randomize the effects of the m_i; alternatively, calibration of all measuring instruments would provide a good degree of control over these variables.

$\eta = \eta(E_{I,}\ \tau_L; T_a, R, e, m_i)$
$T_w = T_w(E_i, \tau_L; T_a, R, e, m_i)$
$I = I(E_i, \tau_L; T_a, R, e, m_i)$

PROBLEM 1.9

KNOWN: Specifications Table 1.1
Nominal pressure of 500 cm H_2O to be measured.
Ambient temperature drift between 18 to 25 ^oC

FIND: Magnitude of each elemental error listed.

SOLUTION

Based on the specifications, the input and output spans (each the difference between the minimum and maximum values of range) are given as

r_i = 1000 cm H_2O
r_o = 5 V

Hence, K = 5 V/ 1000 cm H_2O = 5 mV/cm H_2O = 0.005 V/cm H_2O. This gives a nominal output at 500 cm H_2O input of 2.5 V. This assumes that the input/output relation is linear over range but we are told that it is linear to within some linearity error.

linearity error uncertainty = u_L = (0.005) (1000 cm H_2O)

= 5.0 cm H_2O
= 0.025 V

hysteresis error uncertainty = u_h = (0.0015)(1000 cm H_2O)

= 1.5 cm H_2O
= 0.0075 V

sensitivity error uncertainty = u_K = (0.0025)(500 cm H_2O)

= 1.25 cm H_2O = 0.00625 V

thermal sensitivity error uncertainty = (0.0002)(7^{o}C)(500 cm H_2O)

= 0.7 cm H_2O
= 0.0035 V

thermal drift error uncertainty = (0.0002)(7^{o}C)(1000 cm H_2O)

= 1.4 cm H_2O
= 0.007 V

overall instrument uncertainty = $(5^2+1.5^2+1.25^2+0.7^2+1.4^2)^{1/2}$ = 5.6 cm H_2O

COMMENT: When one uncertainty is notably larger than the others, it will dominate the overall uncertainty. Hence, it is important to identify the major sources of error in a measurement. If the uncertainty is smaller by an order of magnitude, you can neglect it.

PROBLEM 1.10

KNOWN: Full scale output = FSO = 1000 N (this is also the value of the output "span")

FIND: u_c

SOLUTION

From the given specifications, the elemental errors are estimated by:

$u_L = 0.001 \times 1000N = 1N$
$u_H = 0.001 \times 1000N = 1N$

$u_K = 0.0015 \times 1000N = 1.5N$
$u_z = 0.002 \times 1000N = 2N$

The overall instrument error is estimated as:

$u_c = (1^2 + 1^2 + 1.5^2 + 2^2)^{1/2} = 2.9$ N

COMMENT

This root-sum-square (RSS) method provides a "probable" estimate (i.e. the most likely estimate) of the uncertainty in the instrument error possible in any given measurement.

"Possible" is a key concept here as the error values will likely change between individual measurements. Uncertainty gives an interval within which the actual error falls with some level of likelihood or probability (such as in 19 measurements out of 20, or 95% of the measurements, we expect the error to be within the interval).

PROBLEM 1.11

SOLUTION

Randomization is used to break-up the effects of interference from either continuous or discrete extraneous (i.e. uncontrolled) variables.

A key independent variable of a particular process is to be increased incrementally over 5 settings of value, ranging from a minimum to a maximum value. Randomizing the order of the settings for the test will break up any potential trends imposed by extraneous effects influenced by the order of application.

PROBLEM 1.12

SOLUTION

Repetition through repeated measurements made under a fixed set of operating conditions provides a measure of the time (or spatial) variation of a measured variable.

Repetition refers to repeating the measurement during a test.

Example: A test is conducted in which a variable is measured multiple times (N) under some condition.

Replication through an independent duplication of tests conducted under similar operating conditions. It provides a measure of the control of the test conditions on the measured variable.

Replication refers to repeating the test (recreating a new data set of repeated measurements).

Example: A test is conducted in which a variable is measured multiple times under some test condition. After reviewing the data, it is decided to repeat the test. The test is setup again and the measurements repeated. This second test is a replication of the first.

In engineering, the term replication is often also applied to tests conducted for purposes of estimating reproducibility of the results – the ability to reproduce a test outcome when conducted by an independent operator, different test lab, or even a different tested device (of the same make and model). The term "reproducibility" explicitly refers to such.

The term replication can have different meanings depending on how it is applied. This is particularly true in statistical studies.

PROBLEM 1.13

FIND: Test matrix to correlate thermostat setting with average room setting

SOLUTION

Although there is no single test matrix, one method of solution follows.

Assume that average room temperature, T, is a function of actual thermostat setting, spatial distribution of temperature, temporal temperature distribution, and thermostat location. We might imagine that for a controlled (fixed) thermostat location, a direct correlation between setting and T could be achieved. However, factors could influence the temperature measured by the thermostat such as sunlight directly hitting the thermostat or the wall on which it is attached or a location directly exposed to furnace forced convection, a condition aggravated by air conditioners or heat pumps in which delivered air temperature is a strong function of outside temperature. Assume a proper location is selected and controlled.

Further, the average room temperature must be defined because local room temperature will vary will position within the room and with time. For the test matrix, the room should be divided into equal areas with temperature sensing devices placed at the center of each area. The output from each sensor will be averaged over a time period that is long compared to the typical furnace on/off cycle.

Select four temperature sensors: A, B, C, D. Select four thermostat settings: s_1, s_2, s_3, s_4, where $s_1 < s_2 < s_3 < s_4$. Temperatures are to be measured under each setting after the room has adjusted to the new setting. One matrix might be:

BLOCK

1 s_1: A, B, C, D
2 s_4: A, B, C, D
3 s_3: A, B, C, D
4 s_2: A, B, C, D

Note that the order of set temperature has been shuffled to attempt to randomize the test matrix (hysteresis is a common problem in thermostats). The four blocks will yield the average temperatures, T_1, T_4, T_3, T_2. The data can be presented in a form of T versus s.

PROBLEM 1.14

FIND: Test matrix to evaluate fuel efficiency of a production model of automobile

ASSUMPTIONS: Automobile model design is fixed (i.e. neglect options). Require representative estimate of efficiency.

SOLUTION

Although there is no single test matrix, one method of solution follows. Many variables can affect auto model efficiency: e.g. individual car, driver, terrain, speed, ambient conditions, engine model, fuel, tires, options. Whether these are treated as controlled variables or as extraneous variables depends on the test matrix. Suppose we "control" the options, fuel, tires, and engine model, that is fix these for the test duration. Furthermore, we can fix the terrain and the ambient conditions by using a mechanical chassis dynamometer (a device which drives the wheels with a prescribed mechanical load) in an enclosed, controlled environment. In fact, such a machine and its test conditions have been specified within the U.S.A. by government test standards. By programming the dynamometer to start, accelerate and stop using a preprogrammed routine, we can eliminate the effects of different drivers on different cars. However, this test will fail to randomize the effects of different drivers and terrain as noted in the government statement "... these figures may vary depending on how and where you drive ... ." This leaves the car itself and the test speed as independent variables, x_a and x_b, respectively. We defer considering the effects of the instruments and methods used to compute fuel efficiency until a later chapter, but assume here that this can be done with sufficient accuracy.

With this in mind, we could choose three representative cars and three speeds with the test matrix:

BLOCK

1 x_{a1}: x_{b1}, x_{b2}, x_{b3}
2 x_{a2}: x_{b1}, x_{b2}, x_{b3}
3 x_{a3}: x_{b1}, x_{b2}, x_{b3}

Note that since slight differences will exist between cars that cannot be controlled, the autos are treated as extraneous variables. This matrix randomizes the effects of differences between cars at three different speeds and yields a curve for fuel efficiency versus speed.

As an alternative, we could introduce a driver into the matrix. We could develop a test track of fixed (controlled) terrain. And we could have three drivers drive three cars at three different speeds. This introduces the driver as an extraneous variable, noted as A_1, A_2 and A_3 for each driver.

Assuming that the tests are run under similar ambient conditions, one test matrix may be

	x_{a1}	x_{a2}	x_{a3}
A_1	x_{b1}	x_{b2}	x_{b3}
A_2	x_{b2}	x_{b3}	x_{b1}
A_3	x_{b3}	x_{b1}	x_{b2}

PROBLEM 1.15

SOLUTION:

Test stand:

Here one would operate the engine under simulated conditions similar to those encountered at the track – such as anticipated engine RPM and engine load (load: estimated mechanical loads on the engine due to mechanical losses, tire rolling resistance, aerodynamic resistance, etc.).

Measure:
- fuel and air consumption
- torque and power output
- exhaust gas temperatures to set air: fuel ratio

Track:

Here one would operate the car at conditions similar to those anticipated during the race.

Measure:
- lap time
- wind and temperature conditions (to normalize lap time)
- depending on team other factors can be measured to estimate loads on the car and car behavior. *Clemson Motorsports Engineering has been active in test method development for professional race teams.*

Obvious major differences:

- Environmental conditions, which effect engine performance, car behavior and tire behavior.
- Engine load on a test stand is well-controlled. On track, the driver does not execute exactly on each lap, hence varies load such as due to differences in drive path 'line' and this affects principally aerodynamic loads and tire rolling resistance. Incidentally, all of these are coupled effects in that a change in one affects the values of the others.
- Ram air effect of moving car can be simulated but difficult to get exactly
- Each engine is an individual. Even slight differences affect handling and therefore, how a driver drives the car (thus changing the engine load).

PROBLEM 1.16

KNOWN: Ideal gas model is applied

FIND: Is it correct?

SOLUTION

Validation refers to determining if an assumed model correctly applied to the real process.

In this case, the assumption is that the particular gas used in a test behaves as an ideal gas:

$$p = \rho RT$$

where absolute pressure is related directly to the gas density and the absolute temperature of the gas. The value ‘R’ is a gas constant, which is related directly to the molecular weight of the gas.

A test of this model could involve measurements of two of the three independent variables: temperature, pressure, and/or density. The third variable would be measured and compared to the model prediction. This can be done over a range of values to determine suitability of the model for the intended application.

PROBLEM 1.17

KNOWN: Mars Climate Orbiter

FIND: Verification tests to prevent accident

SOLUTION

The Mars Climate Orbiter met its demise due to a conflict in the different unit systems used to develop its on-board thrust propulsion system commands and its ground-based thrust propulsion system commands. The two systems were developed separately by two different vendors and tests had been performed separately by each vendor to ensure their system functioned correctly.

Performing functionality tests on the intended on-board systems using the intended ground-based system prior to the spacecraft being prepared for launch would have identified the problem that the two software algorithms were developed using different unit-systems.

This would be a verification test, one that ensured that the systems were behaving correctly when communicating with each other. Both systems worked and there was no advantage to one unit system over the other. The problem was that they did not work with each other. Systems-level verification would have identified the problem, which was an easy programming fix.

PROBLEM 1.18

KNOWN: Four lathes, 12 machinists are available to produce batches of machine shafts.

FIND: Test matrix to estimate the tolerances held within a batch

SOLUTION

If we assume that batch precision, P, is only a function of lathe and machinist, then

$$P = f(\text{lathe, machinist})$$

We can set up a test matrix using all four lathes, L_1, L_2, L_3, L_4, and all 12 machinists, A, B, ..., L. The machinists are randomly assigned.

BLOCK

1 L_1: A, B, C
2 L_2: D, E, F
3 L_3: G, H, I
4 L_4: J, K, L

Data from each lathe should be indicative of the precision associated with each lathe and the total ensemble of data indicative of batch precision. However, this test matrix neglects the effects of shift and day of the week.

One method which treats machinist and lathe as extraneous variables and reduces test size selects 4 machinists at random. Suppose more than one shaft size is produced at the plant. We could select 4 shaft diameters, D1, D2, D3, D4 and set up a Latin square matrix:

	L_1	L_2	L_3	L_4
B	D1	D2	D3	D4
E	D2	D3	D4	D1
G	D3	D4	D1	D2
L	D4	D1	D2	D3

Note that neither matrix includes shift or day of the week effects and these could be incorporated in an expanded test matrix.

PROBLEM 1.19

SOLUTION

Linearity error

A random static calibration over a specified range will provide the input-output relationship between y and x (i.e. y = f(x)). A first-order curve fit to this data, for example using a least squares regression analysis, will provide the fit $y_L(x)$. The linearity error is simply the difference between the measured value of y at any value of x and the value of y_L predicted by the fit at that x. The uncertainty value assigned as linearity error is defined by the range of these error values over span.This might be the maximum deviation or some statistical measure.

A manufacturer may wish to keep the linearity error below some target value and, hence, may limit the recommended operating range for the system for this purpose. In your experience, you may notice that some systems can be operated outside of their specification range but be aware their elemental errors may exceed the manufacturer's stated values.

Hysteresis error

A sequential static calibration over a specified range will provide the input-output behavior between y and x during upscale-only and downscale-only operations. This will tend to maximize any hysteresis in the system. The hysteresis error is the difference between the upscale value and the downscale value of y at any given x. The uncertainty value assigned as hysteresis error is defined by the range of these errors over the span.

PROBLEM 1.20

KNOWN: 4 brands of tires

8 cars of the same make

FIND: Test matrix to evaluate performance

SOLUTION

Tire performance can mean different things but for passenger tires usually refers to braking and lateral load adhesion during wet and dry operations. For a given series of performance tests, performance will depend on tire and car (a tire will perform differently on different makes of cars). For the same make, subtle differences in production models can affect test results so we treat the car as an individual and extraneous variable.

We could select 4 cars at random (1,2,3,4) to test four tire brands (A,B,C,D)

1: A, B, C, D
2: A, B, C, D
3: A, B, C, D
4: A, B, C, D

This provides a data pool for evaluating tire performance for a make of car. Note we ignore the variable of the test driver but this method will incorporate driver variation by testing four cars. Other strategies could be created.

PROBLEM 1.21

KNOWN: Water at 20^{o}C

Q =f(C,A, Δp ,ρ)
C = 0.75; D = 1 m
2 < Q < 10 m^3/min

FIND: Expected calibration curve

SOLUTION

Part of a test matrix is to specify the range of the independent variable and to anticipate the range resulting in the dependent variable. In this case, the pressure drop will be measured so that it is the dependent variable during a static calibration. To anticipate the output range of the calibration then:

Rearranging the known relation,

$$\Delta p = (Q/CA)^2 (\rho/2)$$

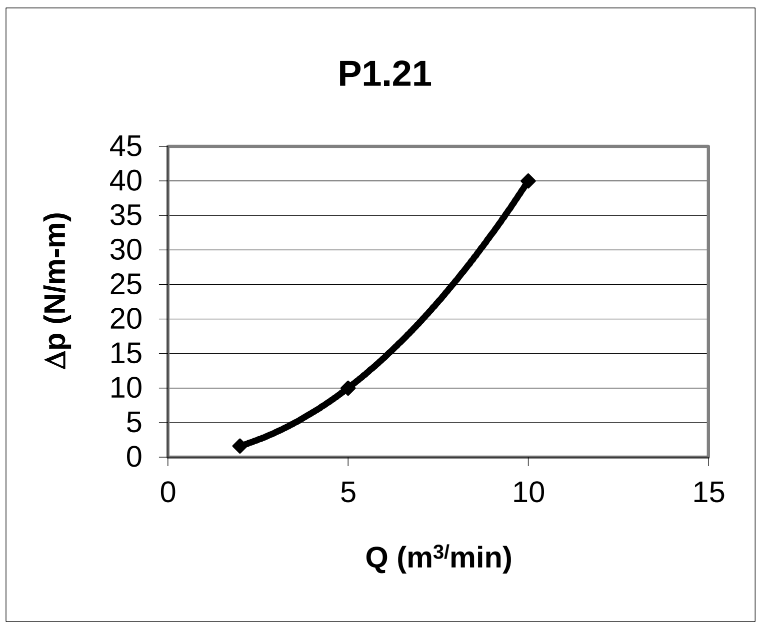
For ρ= 998 kg/m^3 (Appendix B), and A = πD^2/4, we find:

Q (cmm)	Δp (N/m^2)
2	1.6
5	10
10	40

This is plotted below. It is clear that K will not be a constant as

K = f(Q).

$$K = \left[\frac{dp}{dQ}\right]_Q = \frac{\rho Q}{(CA)^2}$$



PROBLEM 1.22

KNOWN: Address issues associated with metering gasoline at the point of delivery to consumers

FIND: Federal standard and cost of errors

SOLUTION

(a) The federal standard requires that a gas pump be accurate to 6 in^3 (0.0983 L ~ 0.1 L) in the delivery of 5 gallons of gas (about 19 L), or an error as large as about 0.50%. In 25 gallons this is 0.13 gallons or in 95 L that's an error of about 0.5 L.

(b) With a fleet average for passenger cars of 30.2 MPG, the maximum value of the error (and still meet legal specifications) in driving 150,000 miles (240,000 km) is $104 if gas costs $4.00.

Testing of a pump for accuracy will vary by location. In many cases, the test is random and infrequent. Of course, if the error is a random error, then we would expect the amount to be high one day and low another day and should even out. But if the error is a systematic error, the error can accumulate high or low. A less ethical vendor will purposely error on the high reading side and pocket the difference.

(c) Suggestions:

- Be suspicious if the pumped volume exceeds your tank volume!

- as a test of your local fuel station, bring a portable fuel can along – these are 5 gallons in the US. Fill to its exact fill line and compare. Remember that by law the difference can be as large as 6 in^3 (or 0.1 L or 0.026 gal) and be considered acceptable, but this amount will be imperceptible against the line. Significant deviations should be retested and, if reoccurring, should be reported.

- if you regularly notice a significant difference in fuel mileage between to different fueling stations, be suspicious of an inaccurate pump.

PROBLEM 1.23

KNOWN: Venturi flowmeter and ASME PTC 19.5

FIND: Describe its use

SOLUTION

A venture flowmeter is an in-line device used to measure volume flow rate of fluids. The device reduces the internal flow area from that of the pipe to a minimum at a throat and then expands back to the pipe area. The approach is to measure the pressure change between upstream pressure in the pipe and the pressure at the throat. The difference is proportional to the volume flow rate.

Standard PTC 19.5 provides specifications for venture design and use.

In operation, measuring the dp determines the flow rate. Alternatively, setting the pressure drop, dp, sets the volume flow rate.

Independent variable: dp

Dependent variable: Q

PROBLEM 1.24

SOLUTION

Controlled variables

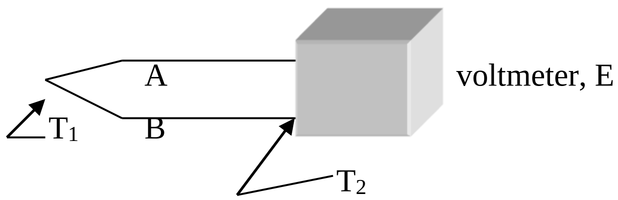
A and B (i.e. control the materials of two alloys)
T_2 (reference junction temperature)

Independent variable

T_1 (measured temperature)

Dependent variable

E (output voltage measured)



PROBLEM 1.25

SOLUTION

LVDT calibration

Independent variables

micrometer setting (i.e. the applied displacement)

Controlled variable

power supply input to LVDT

Dependent variable

LVDT output voltage measured

Extraneous variables

operator set-up (zeroing of micrometer with LVDT zero)

In practice, the LVDT is used to measure displacement within a system. The LVDT output voltage could be an independent variable in such a measurement scheme. For example, this is the case if the LVDT is used to measure the spring displacement in a mass-spring-damper vehicle suspension system in which the mass (vehicle) displacement is the dependent variable.

COMMENT

If you try this you will find that the power supply excitation voltage can influence on the results. The ability to provide the exact voltage on replication is important in obtaining consistent results in many transducers. Even if you use a regulated laboratory variable power supply, this effect can be seen in your data variation on replication as a random variation. If you use an unregulated source, be prepared to trace these effects as they change from hour to hour or from day to day.

Many LVDT units allow for use of DC power, which is then passed through a transformer converting to the AC form before being applied to the coil. It is easiest to see the effect of power setting on the results when using this type of transducer.

PROBLEM 1.26

SOLUTION

To test for repeatability in the LVDT, we might displace the core to various random values over a selected range, such as its expected range, and develop a data base. Data scatter about a curve fit will provide a measure of repeatability for this instrument (methods are discussed in Chapter 4).

Reproducibility involves re-testing the system at a different facility or something equivalent to this, such as using different instruments or test fixtures. Think of this as a test duplication, to be able to reproduce test results. Even though a similar procedure and test matrix will be used to test for reproducibility, the duplication involves different facilities, individual instruments, and test fixtures. A reproducibility test is a special type of replication – by using the different facility constraint added. The combined results allow for interference effects to be randomized.

Bottom Line: The results leading to a reproducibility specification are more representative of what can be expected by the end user (YOU!).

PROBLEM 1.27

SOLUTION:

(i) Running the car on a chassis dynamometer, which applies a desired load to the wheels as the car is operated at a desired speed so as to simulate the car being driven, provides a controlled test environment for estimating fuel consumption. The operating loads form a 'load profile' to simulate the road course.

Allowing a driver to operate a car over a predetermined course provides a realistic simulation of expected consumption. No matter how well controlled the dynamometer test, it is not possible to completely recreate the driving situation that a real driver provides. However, each driver will drive the course a bit differently.

Extraneous variables include: individual entities of driver and of car that affect consumption in either method; road variations and differences between the test methods; road or weather conditions (which are both variable) that change the simulation.

(ii) The dynamometer test is well controlled. In the hands of a good test engineer, valuable information can be ascertained and realistic mileage values obtained. Most important, testing different car models using a predetermined load profile forms an excellent basis for comparison between car makes – this is the basis of a 'standardized test.'.

The variables in a test affect the accuracy of the simulation. Actual values obtained by a particular driver and car are not tested in a standardized test.

(iii) If the two methods are conducted to represent each other, than these are concomitant methods. Even if not exact representations, information obtained in one can be used to get realistic estimates to be expected in the other. For example, a car that gets 10 mpg on the chassis dynamometer should not be expected to get 20 mpg on the road course.

PROBLEM 1.28

KNOWN: $C_R = \sqrt{h/H}$ (calculated)

h = bounce height (measured)

H = initial height (measured)

SOLUTION:

Spikes in volleyball at the collegiate level may have velocities of 30 m/sec. However, the terminal velocity of a volleyball may be computed from

$$V_t = \sqrt{\frac{2mg}{\rho_{air} A C_d}}$$

where we take the mass of the volleyball to be 0.28 kg, the density of air to be 1 kg/m^3 and the drag coefficient to be 0.5. This yields a terminal velocity below 20 m/sec.

Therefore a reasonable approach might be to drop the volleyball from heights of 5, 10 and 15 m and determine C_R. Examining the data would show a trend from which we could estimate the limiting value of C_R with increasing speed.

PROBLEM 1.29

KNOWN: $C_R = \sqrt{h/H}$ (calculated)

h = bounce height (measured)

H = initial height (measured)

SOLUTION:

A ball dropped from a fixed height, H, will have an impact velocity of $v_i = \sqrt{2gH}$ where g is the local acceleration of gravity at the location of the test. As $v_f = \sqrt{2gh}$, the ratio $C_R = \sqrt{h/H} = v_f / v_i$.

So the variables are: H, h, v_i, v_f, C_R, and g.

Independent variables: H

Dependent variables: h

equivalently, the calculated variables : v_i, v_f, C_R could be considered as dependent variables

Parameters: g and, assuming the test plan calls for repeated measurements from a controlled and fixed height H, the variable H could also be considered as a parameter.

Measured variable: h

You should be able to conceptualize how the scatter in the results for h would be affected by how well H is controlled. H is a controlled variable.