A Systematic Approach for Instrumentation of a Mechatronic System

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Abstract: This paper deals with instrumenting a mechatronic system, through the incorporation of suitable sensors, actuators, and other required hardware. Sensors (e.g., semiconductor strain gauges, tachometers, RTD temperature sensors, cameras, piezoelectric accelerometers) are needed to measure (sense) unknown signals and parameters of a system and its environment. The information acquired in this manner is useful in operating or controlling the system, and also in process monitoring; experimental modeling (i.e., model identification); product testing and qualification; product quality assessment; fault prediction, detection and diagnosis; warning generation; surveillance, and so on. Actuators (e.g., stepper motors, solenoids, dc motors, hydraulic rams, pumps, heaters/coolers) are needed to "drive" a plant. Control actuators (e.g., control valves) perform control actions, and in particular they drive control devices. Micro-electromechanical systems (MEMS) use microminiature sensors and actuators. MEMS sensors commonly use piezoelectric, capacitive, electromagnetic and piezoresistive principles. MEMS devices provide the benefits of small size and light weight (negligible loading errors), high speed (high bandwidth), and convenient mass-production (low cost). The process of instrumentation involves the identification of proper sensors, actuators, controllers, signal modification/interface hardware, and software with respect to their functions, operation, parameters, ratings, interaction with each other, so as to achieve the performance requirements of the overall system, and interfacing/integration/tuning of the selected devices into the system, for a given application. This paper presents the key steps of instrumenting a mechatronic system, in a somewhat general and systematic manner. Examples are described to illustrate several key procedures of instrumentation.

Key words: Instrumentation, mechatronic systems, sensors, actuators, signal modification, impedance matching, system integration, performance specification, rating parameters.

1 Mechatronic Instrumentation

The subject of Mechatronics concerns the synergistic application of mechanics, electronics, controls, and computer engineering in the development of multiphysics (e.g., electromechanical, electrohydraulic, electrothermal) products and systems, through an integrated design approach. Mixed-domain (or multi-domain or multiphysics) systems incorporate several physical domains such as electrical, mechanical, fluid, and thermal, in an integrated manner [1]. For example, an antilock braking system (ABS) of an automobile may involve mechanics, electronics, hydraulics, and heat transfer, and may be designed in an "optimal" manner as a mechatronic product. Examples of mechatronic products and systems are modern automobiles and aircraft, smart household appliances, medical robots, space vehicles, and office automation devices.

A typical mechatronic system consists of a mechanical skeleton, actuators, sensors, controllers, signal conditioning/modification devices, computer/digital hardware and software, interface devices, and power sources. Different types of sensing, information acquisition and transfer are involved among all these various types of components. For example, a servomotor, which is a motor with sensory feedback for accurate generation of complex motions, consists of mechanical, electrical, and electronic components. Its main mechanical components are the rotor, stator, bearings, mechanics of the speed sensor such as an optical encoder, and the motor housing. The electrical components include the circuitry for the field windings and rotor windings (not in the case of permanent-magnet rotors), and circuitry for power transmission and commutation (if needed). Electronic hardware includes what is needed for sensing (e.g., signal generation and shaping in an optical encoder for motion sensing), signal conditioning, and control. The overall design of a servomotor can be improved by taking a mechatronic approach, where all components and functions are treated concurrently in an integrated manner in its design. Considerations of sensing, actuation, component interconnection, signal modification, performance specification, sensitivity analysis, and accuracy considerations are all important in the instrumentation of a mechatronic system, and are discussed in this paper.

1.1 Mechatronic Approach

From a mechatronic viewpoint, a somewhat "optimal" and unified approach, not a sequential approach, has to be taken in the instrumentation process. Specifically, the task of "instrumentation" has to be treated as an integral aspect of the task of "design." Traditionally, a "sequential" approach has been adopted in the design of mixed-domain (or, multiphysics) systems. For example in an electromechanical system, first the mechanical and structural components are designed, next electrical and electronic components are selected or developed and interconnected, subsequently a computer or a related digital device is selected and interfaced with the system, along with a digital controller, and so on. However, in view of dynamic coupling between various components of a system, an accurate design of the system should consider the entire system as a whole rather than designing different domains separately and sequentially.

The need for an integrated and concurrent design for multiphysics systems can be identified as a primary justification for the use of the "mechatronic" approach. In particular, when incorporating instrumentation in the design process, such a unified and integrated approach is desirable with regard to sensors, actuators, controllers, and other hardware. For example, consider the design and development of a sensor jacket for a telemedicine system [2]. Recent advances in sensor technologies that are applicable in human health monitoring such as biomedical nano-sensors, piezoelectric sensors, force and motion sensors, and optical/vision sensors for abnormal motion detection of humans, may be incorporated into the jacket. However, for optimal performance, the selection/development, location, mounting, and integration of the sensors should not be treated independently of the development of other aspects of the jacket. For example, a mechatronic design quotient (MDQ) may be employed to represent the "goodness" of the overall design [3, 4] of the jacket where a design index is defined with respect to each design requirement (e.g., size, structure, components, cost, accuracy, speed). Then, parameters such as sensor size, interface hardware, power requirements, component location and configuration may be included in the MDQ, which will improve/optimize the process of signal acquisition and processing, body conformability, comfort, weight, robustness and cost.

1.2 Instrumentation Steps

The steps involved in instrumentation will depend on the specific engineering system and the performance requirements. But, as a general guideline, some basic steps can be stated as follows [5, 6]:

1 Study the instrumented system (plant)

2 Identify and group the components (possibly, according to the physical domain—mechanical, electrical, fluid, thermal, etc.)

3 Develop a preliminary system architecture

4 Formulate physical equations (Model)—for computer simulation, design, control, etc.

5 Indicate operating requirements (performance specifications) for the plant

6 Identify constraints related to cost, size, weight, environment, etc. (e.g., operating temperature, humidity, dust-free or clean room conditions, lighting, wash-down needs)

7 Select the type and the nature of sensors/

transducers, actuators, and signal modification devices (including interfacing and data acquisition hardware and software, filters, amplifiers, modulators, analog to digital converters—ADC, digital to analog converters—DAC, etc.)

8 Establish the associated ratings/specifications of components (signal levels, bandwidths, accuracy, resolution, dynamic range, power, torque, speed, temperature, and pressure characteristics, etc.)

9 Identify manufacturers/vendors for the components (model numbers, data sheets, etc.)

10 Revise the system architecture (include controllers and/or control schemes if necessary). Revise the original computer model as necessary

11 Carry out computer simulations. Make modifications to instrumentation until the system performance meets the specifications (A mechatronic optimization scheme may be used here)

12 Once acceptable results are achieved, acquire and integrate the actual components. Some new developments or modifications may be needed (new or modified sensors, actuators, interface hardware, fixtures, software, etc.)

2 Instrument Ratings

Definitions of rating parameters that are used by manufacturers and vendors of instruments are in some cases not the same as the analytical definitions provided in books. This is particularly true in relation to the terms linearity and stability. Nevertheless, instrument ratings provided by manufacturers and vendors are very useful in the selection, installation and interconnection, operation, and maintenance of components in a mechatronic system. Some key performance parameters are presented now.

2.1 Rating Parameters

Typical rating parameters provided by instrument manufacturers and vendors (in their data sheets) are the following:

1. Sensitivity and sensitivity error
2. Signal-to-noise ratio
3. Dynamic range (useful operating range)
4. Resolution (smallest meaningful change)
5. Offset or bias
6. Linearity
7. Zero drift, full scale drift, and calibration drift (stability)
8. Useful frequency range (operating bandwidth)
9. Bandwidth (speed, operating frequency range, static range)
10. Input and output impedances

Some of these parameters are further explored now.

2.2 Sensitivity

The *sensitivity* of a device (e.g., transducer) is measured by the magnitude (peak, rms value, etc.) of the output signal corresponding to a unit input (e.g., measurand—the quantity that is measured). This may be expressed as the ratio of incremental output and incremental input (e.g., slope of the input-output curve of the device) or, analytically, as the corresponding partial derivative of the input-output relationship. It is clear that the sensitivity is also the gain of the device. In the case of vectorial or tensorial signals (e.g., displacement, velocity, acceleration, strain, force), the direction of sensitivity should be specified as well.

A countless number of factors (including the environment) can affect the output of a device such as a sensor. Then, important objectives of instrumentation with respect to sensitivity would be:

1. Select a reasonable number of factors that have noteworthy sensitivity levels on the device output
2. Determine the sensitivity values (say, relative sensitivities—non-dimensional) for the selected factors
3. Maximize the sensitivity of the device to the desirable factors (e.g., the measured quantity)
4. Minimize the sensitivity of the device to undesirable factors (e.g., thermal effects on a strain reading) or cross-sensitivity.

Cross-sensitivity: This is the sensitivity along the directions that are orthogonal to the primary direction of sensitivity. It is normally expressed as a percentage of direct sensitivity. High direct sensitivity and low cross-sensitivity are desirable in any input - output device (e.g., measuring instrument). Sensitivity to parameter changes and noise has to be small in any device, however, and this is an indication of its robustness. On the other hand, in adaptive control and self-tuning control, the sensitivity of the system to the control parameters has to be sufficiently high. Often, sensitivity and robustness are conflicting requirements.

Sometimes, a sensitivity may be expressed with respect to more than one input variable. For example, suppose that a potentiometric displacement sensor gives an output of 1.5 V for a displacement of 5 cm, and the power supply voltage of the potentiometer (or, its reference voltage) is 10 V. Then the sensitivity of the device may be expressed as 1.5/5.0/10.0 V/cm/V = 30.0 mV/cm/V. Some examples of sensor sensitivities are given in Table 1.

Table 1 Sensitivities of some practical sensors

Sensor	Sensitivity
Blood Pressure Sensor	10 mV/V/mm Hg
Capacitive Displacement Sensor	10.0 V/mm
Charge sensitivity of Piezoelectric (PZT) Accelerometer	110pC/N (pico-coulomb per newton)
Current Sensor	2.0 V/A
DC Tachometer	5± 10% for 1000 rpm
Fluid Pressure Sensor	80 mV/kPa
Light Sensor (digital output with ADC)	50 counts/lux
Strain gauge (gauge factor)	150 ΔR/R/strain (dimensionless)
Temperature Sensor (Thermistor)	5 mV/K

As another example, consider a photovoltaic light sensor that can detect a maximum of 20 lux of light and generates a corresponding voltage of 5.0 V. Suppose that the device has an 8-bit ADC, which gives its maximum count for the full-scale input of 5.0 V.

The maximum count of the ADC = 2^8 = 256 counts.

This corresponds to a signal of 5.0 V going into the ADC, which is the sensor output for the maximum possible light level of 20 lux. Hence the overall sensitivity of the device is

256/20.0 counts/lux = 12.8 counts/lux.

Note: The sensitivity of the ADC alone is

256/5.0 counts/lux = 51.2 counts/lux.

2.3 Sensitivity Analysis and Error Analysis

Both the sensitivity analysis and the error analysis of a mechatronic system can be done using the same analytical basis. Error analysis, in the present context, involves the determination of how the error in one component of the system affects the performance of another component in the system, and determination of the overall error in the system performance in terms of the errors in the individual components. In analyzing the sensitivity of one parameter/variable on another parameter/variable in a mechatronic system, a small increment (a differential) can be applied to the first parameter/variable and determine the corresponding increment in the second parameter/variable. The ratio of the two increments, in the limit, is in fact the derivative of the second quantity with respect to the first quantity. For error analysis, these increments may be interpreted as the "errors" in the corresponding parameters/variables, and the same analytical procedure as for the sensitivity analysis may be used. Limitations of this approach include the following:

1. An analytical model (or at least an experimental model) must be available, to represent the relationship between various parameters/variables of interest in the system (for determining the corresponding derivatives).

2. The required first derivatives are assumed to exist, which may not be the case in some practical situations (e.g., Coulomb friction, dead zone, saturation, where the derivative is either zero or infinity)

3. The procedure assumes small increments and that the second order terms in a Taylor series expansion are negligible. In other words, only the first derivatives are used, which in fact means the use of a "linear" model. Hence, if the errors or changes in the considered quantities are large, the method can become less accurate or meaningless.

As an example, consider a pressure sensor that uses MEMS technology [7-9] and that is connected to a resistance bridge, as shown in Figure 1. The sensor has a circular diaphragm of radius R and thickness t, which is made of n-silicon (single crystal silicon doped with a donor impurity) of Young's modulus E and Poisson's ratio v. Four MEMS strain gauges of resistance $R1$, $R2$, $R3$, and $R4$ are implanted in the diaphragm as shown so that when a pressure P is applied at the top side of the diaphragm, the resistances $R2$ and $R3$ decrease (due to the compressive strain) while the resistances $R1$ and $R4$ increase (due to the tensile strain). The strain gauges are made of p-silicon (single crystal silicon doped with an acceptor impurity).

The four strain gauges are connected to a resistance bridge of reference dc voltage v_{ref}, as shown in Figure 1. When there is no pressure (i.e., $P = 0$) the diaphragm is unstrained, and the bridge is balanced (i.e., the output voltage v_0 of the bridge is zero). It can be shown that, when a non-zero pressure is present, the bridge output may be expressed as

$$\frac{v_0}{v_{ref}} = \alpha kG\frac{R^2(1-v^2)}{t^2E}P$$

where,

α = diaphragm constant

k = bridge constant = [bridge output]/[bridge output when only one strain gauge is active]

G = gauge factor (sensitivity) of a strain gauge

Expressions (in terms of the parameters in the above sensor equation) for the overall sensitivity of the sensor (i.e., $\frac{\partial v_0}{\partial p}$) and the sensitivity of the sensor for a unit reference voltage, can be determined as follows:

The system model is $\frac{v_0}{v_{ref}} = \alpha kG\frac{R^2(1-v^2)}{t^2E}P$.

This may be expressed as $v_0 = \alpha kG\frac{R^2(1-v^2)}{t^2E}v_{ref}P$.

The overall sensitivity is $\frac{\partial v_0}{\partial P} = \alpha kG\frac{R^2(1-v^2)}{t^2E}v_{ref}$

The following parameter values are given:

$\alpha = 3/8$, $k = 4$, $G = 150.0$, diaphragm radius = 1 mm, diaphragm thickness = 50 μm, $v = 0.25$, Young's modulus = 150.0 GPa, and $v_{ref} = 20.0$ V

It is obtained, $\alpha kG\frac{R^2(1-v^2)}{t^2E}v_{ref} = \frac{3}{8}\times4\times150\times\frac{(1\times10^{-3})^2\times(1-0.25^2)}{(50\times10^{-6})^2\times150\times10^9}\times20.0$ V/Pa

Overall sensitivity =
11.25×10^{-6} V/Pa = 11.25 V/MPa

The sensitivity with respect to a unit reference voltage is $\frac{\partial^2 v_0}{\partial v_{ref}\partial P} = \frac{1}{v_{ref}}\frac{\partial v_0}{\partial P} = \alpha kG\frac{R^2(1-v^2)}{t^2E}$

Substitute the given numerical values:

$\alpha kG\frac{R^2(1-v^2)}{t^2E} = \frac{11.25\times10^{-6}}{20}V/V/Pa = 0.5625\times10^{-6}V/V/Pa = 0.5625$ V/V/MPa

Using the absolute error method it is possible to determine an expression for the fractional error in the bridge output (v_0) in terms of the fractional errors in G, R, t, v, E, v_{ref}, and P.

Note: It is assumed that α and k are error free. The errors in G, R, t, v, E, and v_{ref} are due to sensor error. The error in P comes from such errors as noise and disturbances that enter the process before the pressure signal is measured by the sensor (i.e., they correspond to *process error*).

The system model is $\frac{v_0}{v_{ref}} = \alpha k G \frac{R^2(1-v^2)}{t^2 E} P$

Take the natural logarithm:

$\ln v_0 = \ln\alpha + \ln k + \ln G + 2\ln R - 2\ln t + \ln(1-v^2) - \ln E + \ln v_{ref} + \ln P$

Take the differentials of the individual terms (*Note*: Neglect the differentials of α and k because they do not have errors). It is obtained

$$\frac{\delta v_0}{v_0} = \frac{\delta G}{G} + 2\frac{\delta R}{R} - 2\frac{\delta t}{t} - \frac{2v\delta v}{(1-v^2)} - \frac{\delta E}{E} + \frac{\delta v_{ref}}{v_{ref}} + \frac{\delta P}{P}$$

Or,

$$\frac{\delta v_0}{v_0} = \frac{\delta G}{G} + 2\frac{\delta R}{R} - 2\frac{\delta t}{t} - \frac{2v^2 v}{(1-v^2)}\frac{\delta v}{v} - \frac{\delta E}{E} + \frac{\delta v_{ref}}{v_{ref}} + \frac{\delta P}{P}$$

Hence, the relationship of the fractional errors is

$$e_{v_0} = e_G + 2e_R - 2e_t - \frac{2v^2}{(1-v^2)}e_v - e_E + v_{ref} + e_P .$$

When expressed as absolute values (the errors will be additive regardless of the actual sign), the result is

$$|e_{v_0}| = |e_G| + 2|e_R| + 2|e_t| + \frac{2v^2}{(1-v^2)}|e_v| + |e_E| + |v_{ref}| + |e_P| \qquad (1)$$

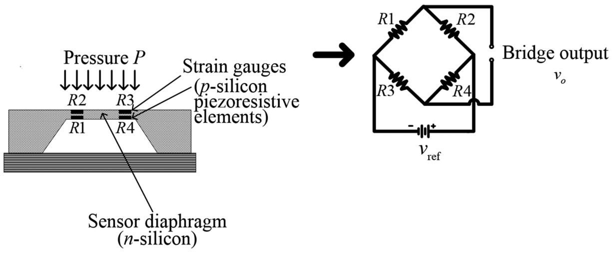

Fig. 1 MEMS-based pressure sensor with a resistance bridge.

3 Component Interconnection

When components are interconnected, the behavior of the individual components in the integrated system can deviate significantly from that when each component operates independently. Specifically, dynamic interactions (dynamic coupling) will take place between them and hence the conditions of either component will be different from what they were before connection. It follows that component interconnection is important in instrumentation (and overall development) of a mechatronic system.

The nature and type of the signals that are present at the interface of the interconnected components depend on the nature and type of the components. For example, when a motor is coupled with a load through a gear (transmission) unit, mechanical power flows at the interfaces of these components. In this example, the power that is transmitted is of the same type (mechanical) and the associated angular velocity and torque are particularly focused. On the other hand, when a motor is connected to its electronic drive system (for example, the electrical dive circuit may be connected to a stator or rotor or both of a dc motor depending on the type of motor), there is conversion of electrical power of the drive circuit into mechanical power of the rotor. Their interface may be represented by an electro-mechanical transformer, as shown in Figure 2. On one side we have voltage and current as the power signals and on the other side we have angular velocity and torque as the power signals. Note: In both these examples, there will be energy dissipation (wastage) on both sides, and hence the energy conversion will not take place at 100% efficiency.

It is clear that the interconnected components should be properly matched for the interconnected system to operate in the desired manner. For example, in the case of a motor and its electronic drive system, maximum efficiency may be a primary objective. Then, the dynamic interaction between the two components will be significant. In contrast, in the case of a sensor and a monitored object, it is important that the dynamic conditions of the object would not be altered by the sensor (i.e., the loading of the object by the sensor should be negligible; for example, with a motion sensor, both electrical loading and mechanical loading should be negligible). In other words, dynamic interaction between the sensor and the monitored object should be negligible while maintaining the ability to accurately measure the required quantity.

The component interface plays an important role in the proper operation of the interconnected system. Specifically, the interface has to be designed, developed, or selected depending on the specific function of the interconnected system. Matching of components in a multicomponent system should be done carefully to improve the system performance and accuracy. In this context impedance considerations are important, because impedance matching is necessary to realize the best performance from the interconnected system, depending on its functional objective.

The following considerations are relevant in component interconnection:

1. Characteristics of the interconnected components (e.g., domain of the component—mechanical, electrical/electronic, thermal, fluid, etc.; type of the component—actuator, sensor, drive circuit, controller, mounting or housing, etc.)

2. Purpose of the interconnected system (e.g., drive a load, measure a signal, communicate information, minimize noise and disturbances—mechanical shock and vibration in particular)

3. Signal/power levels of operation.

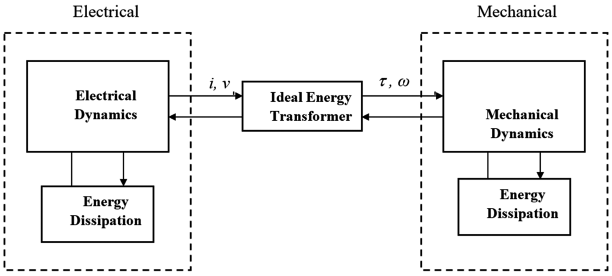

Fig. 2 A model for electro-mechanical component interconnection.

3.1 Signal Modification and Conditioning

For application requirements and for matching of interconnected components, their operating signals may have to be modified. The tasks of signal modification include signal conditioning (e.g., amplification, filtering), signal conversion [e.g., ADC, DAC, voltage-to-frequency conversion, and frequency-to-voltage conversion], modulation [e.g., amplitude modulation (AM), frequency modulation (FM), phase modulation (PM), pulse-width modulation (PWM), pulse-frequency modulation (PFM), and pulse-code modulation (PCM)], and demodulation (i.e., the reverse process of modulation). In addition, many other types of useful signal modification operations can be identified. For example, phase shifting, curve shaping, offsetting, and linearization can also be classified as signal modification.

Particularly for transmission, a signal should be properly modified by amplification, filtering modulation, digitizing, and so on, so that the signal/noise ratio of the transmitted signal is sufficiently large at the receiver. The significance of signal modification is clear from these observations.

3.2 Impedance Considerations

Consider a mechatronic system consisting of several interconnected components. The impedances of the individual components can adversely affect the performance of the overall system. There are several ways how impedance information of the connected devices can be used in procedures of instrumentation. In particular, the impedances of the interconnected components will determine:

1. The amount of power transferred to a load

2. The efficiency of power transfer

3. How much of a signal is transmitted through an impedance discontinuity, in view of signal reflection

4. The level of loading from one component on to another.

Proper instrumentation procedures are able to adjust (match) component impedances so as to:

1. Maximize the amount of power transfer

2. Maximize the efficiency of power transfer

3. Reduce the loading, by making the input impedance of the second component larger than the output impedance of the first component

4. Avoid the signal reflection at a junction of two components (an impedance discontinuity), by making the component impedances equal.

In the impedance analysis of a mechatronic system, the *mobility* of a mechanical device is analogous to the electrical impedance of an electrical device [10]. Specifically,

$$\text{Mobility} = \frac{\text{Generalized Velocity}}{\text{Generalized Force}} = \frac{\text{Across-varoable}}{\text{Through-variable}}$$

$$\text{Electrical Impedance} = \frac{\text{Voltage}}{\text{Current}} = \frac{\text{Across-varoable}}{\text{Through-variable}}$$

Hence, the two are analogous, and they will provide analogous circuit structures (i. e., Parallel mechanical-component connections will be analogous to parallel electrical-component connections; Series mechanical-component connections will be analogous to series electrical-component connections.

As an illustrative example in the electrical domain, consider the lumped-parameter model (equivalent circuit) of an electric cable, as shown in Figure 3(a). The circuit consists of an inductor of inductance L_c, a resistor of resistance R_c, and a capacitor of capacitance C_c. Suppose that this cable is connected to an electric source of voltage v_s and internal impedance Z_s. The corresponding circuit is shown in Figure 3(b). In terms of the impedances indicated in Figure 3(b) it is now possible to determine the *input impedance* and the *output impedance* of this circuit, which consists of the input source and the cable.

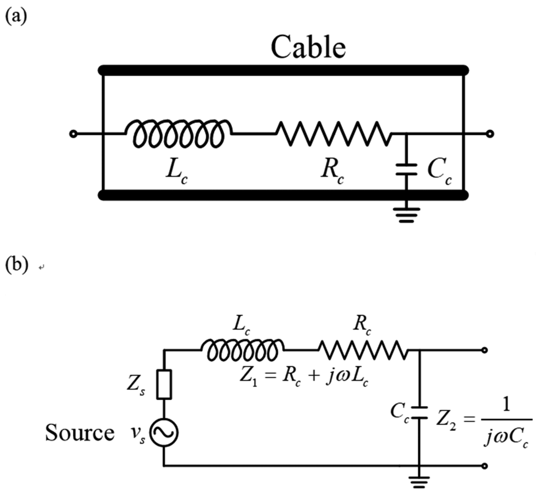

Fig. 3 (a) Equivalent circuit of an electric cable; (b) Circuit of a voltage source with a connected cable.

Input Impedance:

Maintain the output of the system in open circuit, as shown in in Figure 4(a).

Voltage at the input $= v_s$

Current at the input $i_i = \frac{v_s}{Z_s + Z_1 + Z_2}$

Input impedance $Z_i = \frac{v_s}{i_i} = Z_s + Z_1 + Z_2$

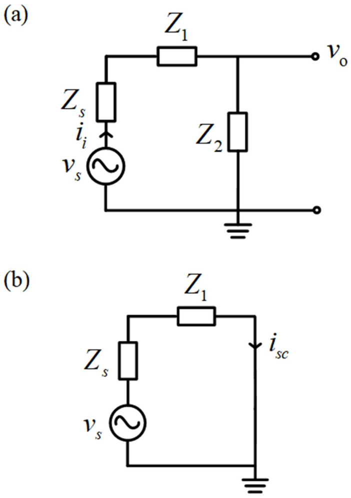

Fig. 4 The system with its output, (a) in open circuit, (b) in short circuit.

Output Impedance:

Voltage at the output, in open circuit (See Figure 4(a); note the voltage divider)

$$v_o = \frac{Z_2}{Z_s + Z_1 + Z_2} v_s$$

Maintain the output of the system in short circuit, as shown in in Figure 4(b).

Short-circuit current at the output, $i_{sc} = \frac{v_s}{Z_s + Z_1}$

Output impedance

$$Z_o = \frac{v_o}{i_{sc}} = \frac{Z_2 v_s}{Z_s + Z_1 + Z_2} \times \frac{Z_s + Z_1}{v_s} = \frac{Z_2(Z_s + Z_1)}{Z_s + Z_1 + Z_2}$$

Next let us consider an example in the mechanical domain. A simplified quarter-model of a vehicle is shown in Figure 5(a). The model parameters are mass m, stiffness k, and damping constant b. The input vertical velocity (at the tires) from the road disturbances is $v(t)$. The output is the velocity v_m of the vehicle compartment.

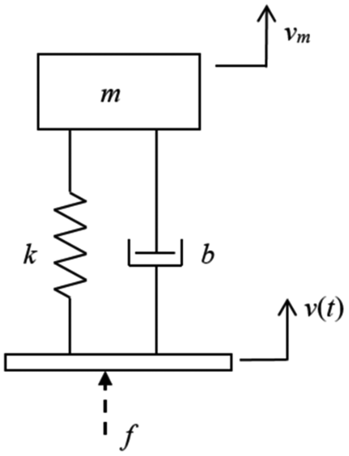

Fig. 5(a) A quarter model of a vehicle.

The mobility circuit of this system is shown in Figure 5(b).

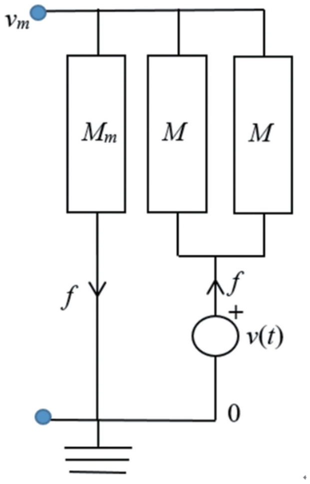

Fig. 5(b) The mobility circuit of the system.

The mobilities of the circuit components are：

$$M_m = \frac{1}{ms}; M_k = \frac{s}{k}; M_b = \frac{1}{b} \qquad (2)$$

Now it is possible to determine the input mobility and the output mobility of the circuit.

Input Mobility：

The combined mobility M_s of the two parallel elements (representing the vehicle suspension) is given by

$$\frac{1}{M_s} = \frac{1}{M_k} + \frac{1}{M_b}$$

Or,

$$M_s = \frac{M_k M_b}{M_k + M_b} = \frac{s/(kb)}{s/k + 1/b} = \frac{s}{bs + k}$$

Since the output is in open-circuit, the input mobility can be directly obtained as

$$M_i = \frac{v}{f} = M_s + M_m = \frac{s}{bs + k} + \frac{1}{ms} = \frac{ms^2 + bs + k}{ms(bs + k)}$$

Note: For convenience, the Laplace (or frequency) domain variables are denoted by the same symbols as their time-domain variables (even though, clearly, the domains are very different).

Output Mobility：

Since in series connection, velocity is divided in proportion to themobilities, the open-circuit output velocity is

$$v_m = \frac{M_m}{(M_m + M_s)} v \qquad (3)$$

The circuit with the output short-circuited is shown in Figure 5(c).

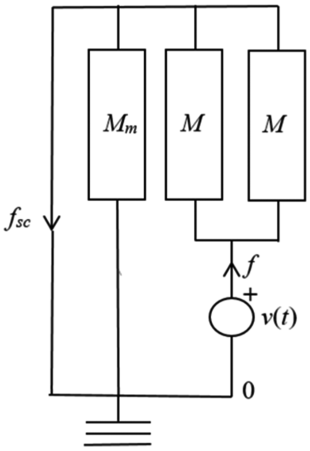

Fig. 5(c) Circuit with the output shorted.

The short-circuit force is

$$f_{sc} = \frac{v}{M_s} \qquad (4)$$

The output mobility (by definition) is (from (3) and (4))：

$$M_o = \frac{v_m}{f_{sc}} = \frac{\dfrac{M_m}{(M_m + M_s)} v}{\dfrac{v}{M_s}} = \frac{M_m M_s}{(M_m + M_s)}$$

$$= \frac{1}{1/M_s + 1/M_m} = \frac{1}{\frac{bs+k}{s} + ms} = \frac{d}{ms^2 + bs + k} \tag{5}$$

Now suppose that a velocity sensor of mass m_s is placed on the vehicle compartment (i.e., at the circuit output), as shown in Figure 5(d). It is possible to determine the mobility introduced by this sensor. Also, it is possible to show that (as expected) in order to reduce mechanical loading by the sensor on the vehicle (i.e., to obtain accurate velocity readings) the sensor mass has to be much smaller than the vehicle compartment mass.

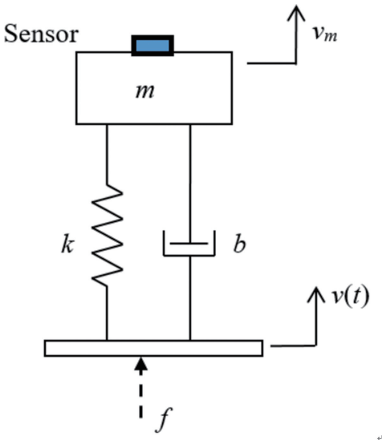

Fig. 5(d) Vehicle with the velocity sensor.

Mobility of the sensor is

$$M'_s = \frac{1}{m_s s} \tag{6}$$

To reduce mechanical loading by the sensor on the vehicle compartment, the ratio $\frac{M'_s}{M_o}$ has to be very small.

From (5) and (6) it is obtained

$$\frac{M'_s}{M_o} = \frac{ms^2 + bs + k}{m_s s^2} = \frac{m}{m_s} + \frac{b}{m_s s} + \frac{k}{m_s s^2}$$

The first term of the three terms on the RHS is dominant because, as the excitation frequency increases, the last two terms go to zero. So, it is clear that, in order to reduce mechanical loading (and improve the accuracy of the measurement), the sensor mass must be much smaller than the object (vehicle compartment) mass.

4 Sensors

There are many types and classes of sensors. Also, advanced sensor technologies are increasingly embedded into mechatronic systems. Selection of proper sensors is crucial in the instrumentation of a mechatronic system. A systematic procedure has to be followed in selecting sensors for a mechatronic application. Some relevant issues are presented in this section.

4.1 Sensor Classification

(a) Based on Physics/Technology

Active: Power for sensing does not come from the sensed object (comes from an external source)

Analog: Output is analog

Digital: Output is digital, pulses, counts, frequency, etc.

Passive: Power for sensing comes from the sensed object

Piezoelectric: Pressure on the sensor element generates an electric charge or voltage

Piezoresistive: Pressure/stress/strain on the sensor element changes its electrical resistance

Photoelastic: Stress/strain on the sensor element changes its optical properties

Broad Classification: Resistive; Capacitive (may include piezoelectric); Inductive (may include magnetic); Electric; Integrated-circuit (IC); Mechanical; Fluid; Optical

(b) Based onMeasurand/Application

Bio-medical: Motion, force, blood composition, blood pressure, temperature, flow rate, urine composition, excretion composition, ECG, breathing sound, pulse, X-ray image, ultrasonic image

Chemical: Organic compounds, inorganic compounds, concentration, heat transfer rate, temperature, pressure, flow rate, humidity

Electrical/Electronic: Voltage, current, charge, passive circuit parameters, electric field, magnetic field, magnetic flux, electrical conductivity, permittivity, permeability, reluctance

Mechanical: Force (effort including torque, tactile), motion (including position and deflection), optical image, other images (X-ray, thermal, acoustic, etc.), stress, strain, material properties (density, Young's modulus, shear modulus, hardness, Poisson's ratio

Thermo-fluid: Flow rate, heat transfer rate, infrared waves, pressure, temperature, humidity, liquid level, density, viscosity, Reynolds number, thermal conductivity, heat transfer coefficient, Biot number, image.

4.2 Innovative Sensor Technologies

Apart from conventional sensors, many types of innovative and advanced sensors are being investigated and developed. Several types are listed below:

1. Microminiature Sensors: IC-based, with built-in signal processing [7-9]

2. Intelligent Sensors: Built-in information preprocessing, learning, reasoning, and decision making to provide high-level knowledge [11]

3. Integrated Sensors: Sensors are *integral* with the components. An embedded system has a microprocessor combined with sensors, embedded within a larger system.

4. Networked Sensors: Nodes or agents of a networked multi-agent system are arranged in a specific *architecture*, and communicate with each other. In a distributed sensor network, there can be significant *geographic separation* between sensor nodes[12].

5. Hierarchical Sensory Architectures: Low level sensory information is preprocessed to meet higher level requirements. They are particularly applicable in hierarchical control where each control layer is serviced by a corresponding sensor layer.

6. Multi-sensor Data Fusion: Combines the data from two or more sensors to improve the sensory decision [13-15]

As a related implementation, consider the dynamic sensor module (a self-propelling multi-sensor robot) shown in Figure 6, which is a node of a dynamic sensor network that has been developed for monitoring the quality of water in a natural environment. Many parameters affect the quality of water. They include temperature, pH value, dissolved oxygen (DO), oxidation-reduction potential (ORP), electrical conductivity, flow rate, turbidity, nitrogen (including nitrates, nitrites, and compounds of ammonia), phosphate content, organic carbon, and various organic matter and bacteria. Each of the sensor nodes is able to monitor five of these parameters [6, 16-17]. The nodes will automatically navigate to the best sensing locations for acquiring the most useful and non-redundant information, based on a pre-developed spatiotemporal map of the monitored region. This map is updated using the newly acquired sensory data. The monitored sensory data are used to compute the quality of water (as a spatial distribution) and the associated trends. Based on that information, decisions can be made in order to make predictions, provide warnings and advisories, and take corrective actions.

4.3 Sensor Selection

The key steps in selecting sensors for a specific application are the following:

(a) Study the application, its purpose, and what quantities (variables and parameters) need to be measured

(b) Determine what sensors are commercially available and what quantities cannot be measured (due to inaccessibility, lack of sensors, etc.)

(c) Match the sensor with the required performance specifications

(d) Acquire and implement the available sensors. If the required sensors are not available, look for alternatives.

If an available sensor cannot measure the required quantity:

1. Estimate the required quantity using other quantities that can be measured (e.g., using an "observer" [6]

2. Develop a new sensor for the purpose, or modify an existing sensor, to have parameters that meet the sensing requirements/specifications.

The overall process involves "matching" a sensor (its ratings) with the application (process requirements/ specifications).

4.4 An Innovative Angular Speed Sensor

A sensing mechanism for measuring the angular speed of a shaft is shown in Figure 7. The shaft whose speed (ω_i) has to be measured, is directly connected to a rigid rotor. The rotor is supported on smooth and leak-proof bearings of the casing whose rotary moment of inertia is J. The rotor rotates in the viscous liquid inside the casing, and the associated rotary viscous damping constant is B. The angle of rotation of the casing is θ_0. This rotation is resisted by a torsional spring of stiffness K. Firmly attached to the casing is the code disk of an optical incremental encoder. The pulse sequence generated by the encoder determines θ_0. We will first obtain the transfer function of the device, relating the output angle θ_0 and the input angular speed ω_i. Next we will study the gain of the sensor, using a numerical example.

The free-body diagram of the casing, which is the rotating element, is shown in Figure 8. The moment of inertia of the encoder disk may be neglected or included in J. The damping torque is proportional to the relative velocity of the two cylinders and is given by $B(\omega_i - \dot{\theta}_0)$. The spring torque is given by $K\theta_0$. Newton's 2nd law (Inertial torque = sum of external torques) for the casing:

$$J\ddot{\theta}_0 = -B(\dot{\theta}_0 - \omega_i) - K\theta_0 \quad \text{Or,} \quad J\ddot{\theta}_0 + B\dot{\theta}_0 + K\theta_0 = B\omega_i$$

To get the transfer function, simply replace the time derivative by the Laplace variable s. It is obtained

$$G(s) = \frac{\theta_0}{\omega_i} = \frac{B}{Js^2 + Bs + K}$$

The denominator polynomial (characteristic polynomial) is

$$Js^2 + Bs + K \longrightarrow s^2 + 2\zeta\omega_n s + \omega_n^2$$

(a) Top view. (b) Back view.

(c) Front-right view. (d) Side view.

Fig. 6 Mobile sensor node of a water quality monitoring network.

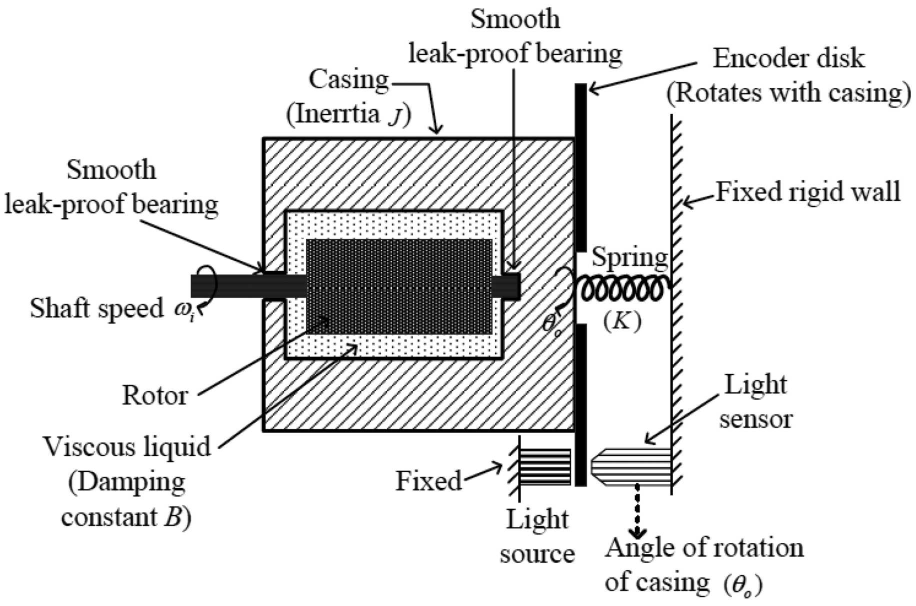

Fig. 7 An innovative sensor for angular speed measurement.

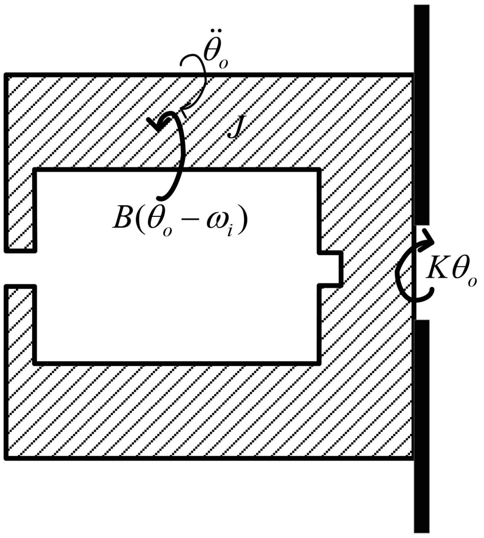

Fig. 8 Free-body diagram of the casing.

Undamped natural frequency $\omega_n = \sqrt{\dfrac{K}{J}}$ (i)

Damping ratio $\zeta = \dfrac{1}{2\omega_n}\dfrac{B}{J} = \dfrac{B}{2\sqrt{KB}}$ (ii)

The frequency-domain transfer function is obtained by setting $s = j\omega$. We have, $G(j\omega) = \dfrac{B}{K - J\omega^2 + jB\omega}$

Static gain = transfer function value at zero frequency $= \dfrac{B}{K}$ (iii)

Time constant $\tau = \dfrac{1}{\zeta\omega_n}$ (iv)

Suppose that it is given $J = 1.0\times10^{-6}$ km · m^2, and it is required that the operating bandwidth of the device be 100 Hz, which is half its undamped natural frequency, and the damping ratio of the measuring device be $\zeta = 0.8$. It is now possible to determine the required values for the torsional spring constant K (N.m/rad) and the viscous damping constant B (N.m/rad/s), in order to meet the indicated specifications. Also, it is possible to determine the corresponding static gain (in units rad/rad/s) of the measuring device.

From (i): Operating bandwidth $= \dfrac{1}{2}\omega_n = \dfrac{1}{2}\sqrt{\dfrac{K}{J}} \rightarrow \dfrac{1}{2}\sqrt{\dfrac{\mathrm{K}}{1.0\times10^{-6}}} = 100\times2\pi \rightarrow$ Torsional stiffness $K = (400\pi)^2 \times 1.0 \times 10^{-6}$ N.m/rad $= 1.58$N.m/rad

From (ii): $\zeta = \dfrac{B}{2\sqrt{KJ}} \rightarrow 0.8 = \dfrac{\mathrm{B}}{2\sqrt{1.58\times1\times10^{-6}}}$ →Damping constant

$B = 1.6 \times \sqrt{1.58 \times 1 \times 10^{-6}} = 2.011 \times 10^{-3}$ N.

m/rad/s

From (iii): Static gain $= \frac{2.011 \times 10^{-3}}{1.58}$ rad/rad/s $= 1.273 \times 10^{-3}$s

The *static gain* is in fact the *sensitivity* of the sensor. Hence it increases the output signal level of the sensor. It is clear as well that, by increasing the natural frequency ω_n of the sensor, it gains the following benefits:

1. Reduces coupling. Thereby the measurement directly depends on the measurand only
2. Reduces dynamic effects (i.e., reduces the frequency dependence of the sensor), thereby increasing the useful frequency range and bandwidth or the speed of response (i.e., reducing the time constant) of the sensor.

4.5 Instrumentation Based on Bandwidth Considerations

In the present context, bandwidth concerns: (a) Speed (or, frequency range) of operation of a device; (b) Rate at which analog signals (e.g., sensory measurements) are sampled or digital control signals are generated. A set of simple steps are given now for developing/ instrumenting a mechatronic system based on bandwidth considerations [6]:

1. Decide on a maximum frequency of operation (BW_o) based on the application requirements
2. Select the process components (electro-mechanical, mechatronic) that have the capacity to operate at least up toBW_o
3. Select feedback sensors with their flat frequency spectrum (operating frequency range) $> 4 \times Bw_o$
4. Develop a digital controller with: (a) Feedback sensor signal sampling rate $> 4 \times BW_o$ (i.e., within the flat spectrum of sensors) and digital control cycle time (control action period) $= 1/(2 \times BW_o)$. *Note*: Then, digital control actions are generated at the rate $2 \times BW_o$
5. Select the control drive system (interface hardware, filters, amplifiers, actuators, etc.) having their flat frequency spectrum $\geqslant Bw_o$
6. Integrate the system and test the performance. If the performance specifications are not satisfied, make necessary adjustments and test again.

5 Actuators

An actuator is a device that mechanically drives a dynamic system. A motor in a robotic manipulator is an example of an actuator. Proper selection of actuators and their drive systems for a particular application is of utmost importance in the instrumentation and design of a mechatronic system. There is a "mechatronic" perspective to the significance of actuators. A typical actuator contains mechanical components like rotors, shafts, cylinders, coils, bearings, and seals, while the controller and drive systems are primarily electronic in nature. Integrated design, manufacture, and operation of these two categories of components are crucial for efficient operation of an actuator. This is essentially a mechatronic problem.

Sensors and actuators are indispensable in a control system. The purpose of the controller is to generate control signals, which will drive the process that is being controlled (called the *plant*) in a desired manner (i.e., according to some *performance specifications*), using various control devices. Specifically in a feedback control system, the control signals are generated based on the sensed response signals of the plant. Sensors, actuators, and other main components in a feedback control system are schematically shown in Figure 9.

Several engineering applications and their use of sensors and actuators are noted in Table 2.

5.1 Actuator Types and Requirements

Broadly there are two types of actuators: *incremental-drive actuators* and *continuous-drive actuators*. Stepper motors, which are driven in fixed angular steps, belong to the class of incremental-drive actuators. They are pulse-driven devices. Each pulse received at the driver of a stepper motor causes it to move by a predetermined, fixed increment of displacement. More common are continuous-drive devices. Examples are direct current (dc) motors, induction motors, hydraulic and pneumatic motors, and piston - cylinder drives (rams). Microactuators are actuators that are able to generate very small (microscale) actuating forces or torques and motions. Typically, they are manufactured through micromachining similar to the production of semiconductor devices.

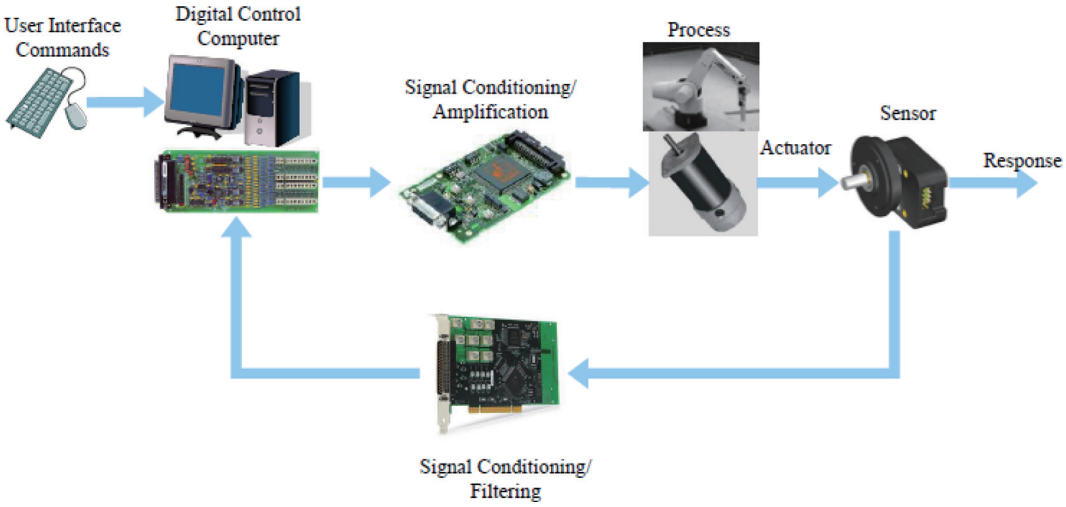

Fig. 9 Sensors and actuators in a feedback control system.

Table 2 Sensors and actuators used in some common engineering applications

Process	Typical Sensors	Typical Actuators
Aircraft	Displacement, speed, acceleration, elevation, angle of attack (pitch), yaw, roll, force pressure, temperature, fluid flow, voltage, current, global positioning system (GPS)	DC motors, stepper motors, relays, valve actuators, pumps, heat sources, jet engines
Automobile	Displacement, speed, force, pressure, temperature, fluid flow, fluid level, vision, voltage, current, GPS, radar, sonar	DC motors, stepper motors, valve actuators, linear actuators, pumps, heat sources
Home Heating System	Temperature, pressure, fluid flow	Motors, pumps, heat sources
Milling Machine	Displacement, speed, force, acoustics, temperature, voltage, current	DC motors, ac motors
Robot	Optical image, displacement, speed, force, torque, tactile, laser, ultrasound, voltage, current	DC motors, stepper motors, ac motors, hydraulic actuators, pneumatic actuators
Wood Drying Kiln	Temperature, relative humidity, moisture content, air flow	AC motors, dc motors, pumps, heat sources

For an actuator, requirements of size, torque or force, speed, power, stroke, motion resolution, repeatability, duty cycle, and operating bandwidth can differ significantly, depending on the particular application and the specific function of the actuator within the mechatronic system. Furthermore, the capabilities of an actuator will be affected by its drive system. Although the cost of sensors and transducers is a deciding factor in low-power applications and in situations where precision, accuracy, and resolution are of primary importance, the cost of actuators can become crucial in moderate to high power control applications. It follows that the proper design and selection of actuators can have a significant economic impact in many applications of mechatronics. The applications of actuators are immense, spanning over industrial, manufacturing, transportation, medical, instrumentation, and household appliance fields. Millimeter-size micromotors with submicron accuracy are useful in modern information storage systems. Distributed or multilayer actuators constructed using piezoelectric, electrostrictive, magnetostrictive, or photostrictive materials are used in advanced and complex applications such as adaptive structures. Other applications of microactuators are found in such domains as biomedical engineering, optics, semiconductor technology, and microfluidics.

5.2 Motor Selection

Torque and speed considerations are crucial in the selection (sizing) of a motor for a particular application. For example, a faster speed of response is possible if a motor with a larger torque-to-inertia ratio is used. The selection of a motor for a specific application is essentially a task of matching the torque-speed requirements (determined by the load) to the available torque-speed capabilities (depend on the motor). The following steps provide some guidelines for the selection process:

Step 1: List the main requirements for the particular application, according to the conditions and specifications for the application. These include operational requirements such as speed, acceleration, and required accuracy and resolution, and load characteristics, such as size, inertia, fundamental natural frequencies, and resistance torques.

Step 2: Compute the required operating torque and speed for the particular application. Newton's second law is the basic equation that is employed in this step. Specifically, the required torque rating is given by

$$T = T_R + J_{eq}\frac{\omega_{\max}}{\Delta t} \qquad (10)$$

where T_R = net resistance torque on the motor, J_{eq} = equivalent moment of inertia (including rotor, load, gearing, dampers, etc.), $\omega_{\max}$ = maximum operating speed, and Δt = time taken to accelerate the load to the maximum speed, starting from rest.

Step 3: Using the torque vs. speed curves (i.e., pull-out curves) for a group of commercially available motors and their drive systems (this information is provided by the motor manufacturer/supplier), select a suitable motor and its drive system. The torque and speed requirements determined in Step 2 should be used in this step.

Step 4: If a motor that meets the requirements is not available, modify the basic design. This may be accomplished by changing the speed and torque requirements by adding devices such as gear systems (e.g., harmonic drive) and amplifiers (e.g., hydraulic amplifiers).

Motors and appropriate drive systems are prescribed in product manuals and catalogs, which are available from the vendors.

5.3 Actuator Sizing Example

Consider the feedback control system of a positioning device as shown in Figure 10. The plant (load) of the system is a mass-spring-damper mechanism of mass M, stiffness K, and viscous damping constant B. The plant is moved by a direct-drive linear dc actuator. The mass of the actuator armature (moving element) is m_a and the viscous damping constant of the actuator is b_a. The armature is directly and firmly attached to the plant mass, as shown in the figure. A linear variable differential transformer (LVDT) with a ferromagnetic core (moving element) of mass m_a is used to measure the displacement x of the plant mass. The carrier voltage in the primary coil of the LVDT is v_{ref} and the carrier frequency is ω_c. The induced voltage in the secondary coil of the LVDT is supplied to a voltage amplifier stage (with resistances R_1 and R_2). The amplified signal is transmitted to a signal multiplier where it is multiplied by the carrier voltage. The product signal goes through a low-pass filter (with resistances R

and R_f, and capacitance C_f). The filter output is the feedback signal, which is subtracted from the reference input u_{ref} of the control system. The resulting error signal e is sampled and digitized through an ADC, and provided to the control computer. The computer generates the digital control signal u_c according a pertinent control scheme. This digital signal is converted into the analog form using a DAC. The resulting analog control signal is properly amplified to generate the necessary current i_a for driving the linear actuator. The force generated by the actuator will drive the plant mass, together with the armature.

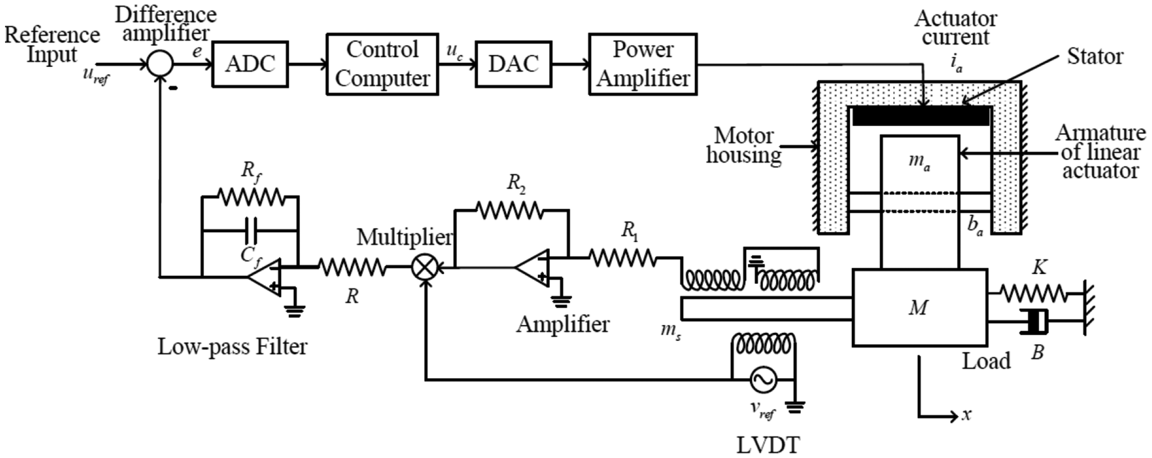

Fig. 10 A feedback control system with a plant driven by a linear actuator.

Suppose that the purpose of the control system is to move the plant mass M through distance d in time T according to a symmetrical, triangular velocity profile (i.e., constant acceleration from rest in the first half time period $T/2$ over distance $d/2$, followed by a constant deceleration to rest in the second half time period $T/2$ over the remaining distance $d/2$).

If the electromagnetic force generated by the linear actuator is $f_a(t)$ and the efficiency of conversion of the electrical power of the linear actuator into mechanical power is η, it is possible to write a differential equation of motion for the displacement x of the plant mass (including the masses of the actuator armature and the LVDT core), with $f_a(t)$ as the input, as follows.

The free-body diagram of the moving mass segment is shown in Figure 11(a). Accounting for the losses after the electromagnetic force is generated by the actuator, the net mechanical force acting on the mass is $\eta f_a(t)$. The damping force is proportional to the velocity $\dot{x}$ of the moving mass, and is given by $(B+b_a)\dot{x}$. The spring force is given by K_x. Newton's 2^{nd} law (Inertial force = sum of external forces) gives:

$$(M+m_s+m_a)\ddot{x} = -(B+b_a)\dot{x} - Kx + \eta f_a(t)$$

$$\text{Or, } (M+m_s+m_a)\ddot{x} + (B+b_a)\dot{x} + Kx = \eta f_a(t)$$

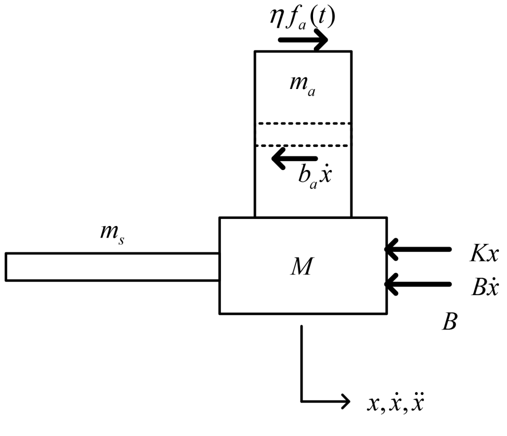

Fig. 11(a) Free-body diagram of the moving mass.

The following numerical values are given for the system parameters: $M = 1.0$ kg, $m_s = 0.01$ kg, $B = 20$ N/m/s, $K = 2500.0$ N/m, $d = 0.02$ m, $T = 1.0$ s. Two linear actuator models are available for this application, whose force versus speed curves (pull-out curves) are shown in Figure 11(b). Also, for Model 1:

$m_a = 0.1$ kg, $b_a = 10.0$ N/m/s, and for Model 2: $m_a = 0.08$ kg, $b_a = 8.0$ N/m/s. For both models, $\eta = 0.9$.

The electromagnetic force required to move the device is given by

$$f_a(t) = \frac{1}{\eta}[(M + m_s + m_a)\ddot{x} + (B + b_a)\dot{x} + Kx]$$

With the given parameter values, it is obtained

$$f_a(t) = \frac{1}{0.9}[(1.01 + m_a)\ddot{x} + (20.0 + b_a)\dot{x} + 2500.0 \times x]$$

Consider the triangular velocity profile of the device, as shown in Figure 11(c).

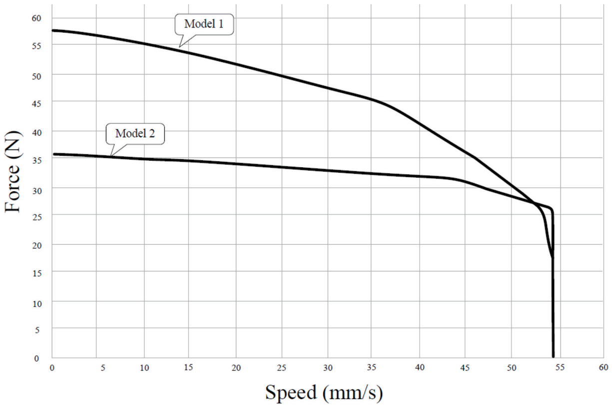

Fig. 11(b) The pull-out curves of two linear motors.

Three critical points of the profile are denoted as A, B, and C.

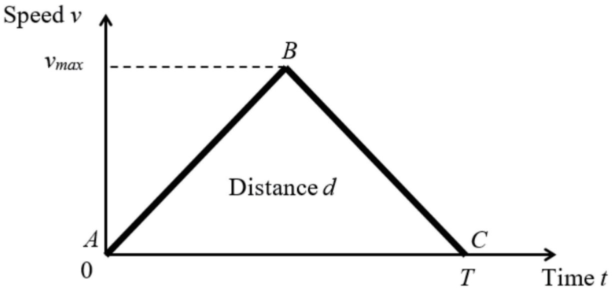

Fig. 11(c) Triangular speed profile.

We have $d = \frac{1}{2}v_{\max}T \quad \rightarrow$

$$v_{\max} = \frac{2d}{T} = \frac{2 \times 0.02}{1.0} = 0.04 \text{ m/s}$$

$$\text{Acceleration } a = \frac{v_{\max}}{T/2} = \frac{0.04}{1.0/2} = 0.08 \text{ m/s}$$

The motion values at the critical points are given below.

Point A: $x = 0, \dot{x} = 0, \ddot{x} = 0.08$ m/s^2

Point B: $x = 0.01, \dot{x} = 0.04, \ddot{x} = 0.08$ m/s^2

Point C: $x = 0.02, \dot{x} = 0, \ddot{x} = 0$

For these three motion points, the available electromagnetic forces from the two actuators are obtained from the given Force vs Speed curves, for the corresponding speed values.

Now it is possible to complete the values as given in Table 3.

Table 3 Values for actuator sizing

Actuator	Model 1	Model 2
m_a(kg)	0.10	0.08
b_a(N/m/s)	10.0	8.0
Point A: Required Force (N)	0.097	0.097
Point A: Available Force (N)	57.5	36.0
Point B: Required Force (N)	29.21	29.12
Point B: Available Force (N)	41.5	32.0
Point C: Required Force (N)	55.6	55.6
Point C: Available Force (N)	57.5	36.0

It is seen that only Model 1 meets or exceeds the required force.

Next, suppose that the operating bandwidth of the plant is twice the undamped natural frequency of the plant (including the masses of the actuator armature and the LVDT core). It is possible to select a suitable value for the carrier frequency ω_c(in Hz) of the LVDT, using the parameters for the selected actuator model (Model 1).

Undamped natural frequency of the system

$$\omega_n = \sqrt{\frac{K}{M + m_s + m_a}} = \sqrt{\frac{2500.0}{1.0 + 0.01 + 0.10}} = 47.46 \text{ rad/s}$$

As given, the operating bandwidth of the system is 2×47.46 rad/s = 94.92 rad/s = 15.11 Hz

Allowing some leeway, use the operating bandwidth value $f_{ob} = 16.0$ Hz

The control bandwidth (both analog hardware and digital control) must be at least equal to this value. Hence, digital control actions must be generated at least at twice this rate (by Shannon's sampling theorem)[5] i.e., at 32.0 Hz. Furthermore, the sensor data has to be sampled into the digital control computer (through ADC) at least at twice this rate; i.e., at 64.0 Hz, in order to generate the control actions at 32.0 Hz (again, by Shannon's sampling theorem). It follows that the sensor (LVDT) signal must have a bandwidth of 64.0 Hz (or more, if the system needs not be "optimal"). The carrier frequency of the LVDT has to be 10 times this value.

Hence, carrier frequency $f_c = 640.0$ Hz or
$\omega_c = 4021.0$ rad/s

In addition to the numerical values given before, suppose that the following values are given: The gain of the voltage amplifier of the LVDT is 10.0; the gain of the low-pass filter is 1.0; $R_1 = 1.0$ kΩ; and $R_1 = 10.0$ kΩ. Now it is possible to determine suitable numerical values for R_2, R_f and C_f.

For the voltage amplifier, gain $= \dfrac{R_2}{R_1} = 10.0.$

With $R_1 = 1.0$ kΩ, it is obtained $R_2 = 10.0$ kΩ

For a single-pole low-pass filter with transfer function $\dfrac{k}{\tau s+1}$, gain $k = \dfrac{R_f}{R} = 1.0.$

With $R = 10.0$ kΩ, it is obtained $R_f = 10.0$ kΩ

The filter has to remove the carrier (640 Hz) but should retain the required bandwidth of the sensor signal (64 Hz). It follows that a filter cut-off frequency of 2×64 Hz $= 128$ Hz $= 128 \times 2\pi$ rad/s would be suitable.

Filter cut-off frequency $= \dfrac{1}{\tau} = \dfrac{1}{R_f C_f}$

Hence, one needs $\dfrac{1}{R_f C_f} = 128 \times 2\pi$

$$\text{Or,} \quad C_f = \frac{1}{128 \times 2\pi \times R_f} = \frac{1}{128 \times 2\pi \times 10 \times 10^3} F = 124.34 \text{ nF}$$

Based on the given numerical values, the following operational parameter values are suitable:

ADC sampling rate = 64 Hz
Digital control action rate = 32 Hz
Digital control bandwidth = 16 Hz

For practical reasons, here it is assumed that the analog control hardware has a bandwidth of at least 16 Hz.

6 Conclusion

This paper concerned instrumenting a mechatronic system, through the incorporation of suitable sensors, actuators, and other required hardware. Proper instrumentation is useful in operating and controlling the system, and particularly in process monitoring; experimental modeling (i.e., model identification); product testing and qualification; product quality assessment; fault prediction, detection and diagnosis; warning generation; and surveillance. Actuators are needed to "drive" a plant. Control actuators perform control actions, and in particular they drive control devices. Micro-electromechanical systems (MEMS) use microminiature sensors and actuators. MEMS sensors commonly use piezoelectric, capacitive, electromagnetic and piezoresistive principles. MEMS devices provide the benefits of small size and light weight (negligible loading errors), high speed (high bandwidth), and convenient mass-production (low cost). The process of instrumentation involves the identification of proper sensors, actuators, controllers, and signal modification/interface hardware and software with respect to their functions, operation, parameters, ratings, and interaction with each other, and interfacing/integration/tuning of them into the system, for a given application, so as to meet a set of performance specifications for the application. This paper presented the key steps of instrumenting a mechatronic system, in a somewhat general and systematic manner. Examples were described to illustrate several key procedures of instrumentation.

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