MISSILE CONTROL

A missile control system consists of those components that control the missile airframe in such a way as to automatically provide an accurate, fast, and stable response to guidance commands throughout the flight envelope while rejecting uncertainties due to changing parameters, unmodeled dynamics, and outside disturbances. In other words, a missile control system performs the same functions as a human pilot in a piloted aircraft; hence, the name *autopilot* is used to represent the pilotlike functions of a missile control system. Missile control and missile guidance are closely tied, and for the purposes of explanation, a somewhat artificial distinction between the two roles is now made. It must be remembered, however, that for a guided missile the boundary between guidance and control is far from sharp. This is due to the common equipment and the basic functional and operational interactions that the two systems share. The purpose of a missile guidance system is to determine the trajectory, relative to a reference frame, that the missile should follow. The control system regulates the dynamic motion of the missile; that is, the orientation of its velocity vector. In general terms, the purpose of a guidance system is to detect a target, estimate missile-target relative motion, and pass appropriate instructions to the control system in an attempt to drive the missile toward interception. The control system regulates the motion of the missile so that the maneuvers produced by the guidance system are followed, thereby making the missile hit or come as close as required to the target. The autopilot is the point at which the aerodynamics and dynamics of the airframe (or body of the missile) interact with the guidance system. Instructions received from the guidance system are translated into appropriate instructions for action by the control devices (e.g., aerodynamic control surfaces, thrust vec-

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

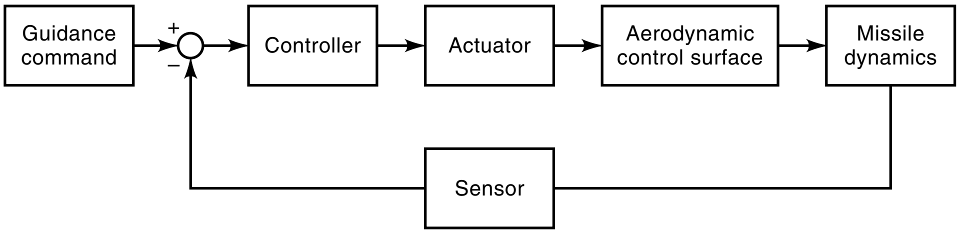

Figure 1. A block diagram describing the functional relations among the components of the missile control system.

toring or lateral thrusters) that regulate the missile's flightpath. A block diagram describing these missile control system operations is depicted in Fig. 1 where the function of each component is further explained as following.

COMPONENTS OF MISSILE CONTROL SYSTEMS

Sensor Units

Sensor units measure some aspects of the missile's motion. Gyroscopes and accelerometers are the two primary sensor units used in any missile control system. They provide the information of rotational and translational motions of a missile, respectively.

1. *Gyroscope.* A gyroscope is a mechanical device containing an accurately balanced rotor with its spin axis passing through the center of gravity. When the rotor rotates at a high speed, it assumes the rigidity characteristics that resist any force tending to displace the rotor from its plane of rotation. The tendency of a gyroscope to maintain its spin direction in the inertial space allows us to measure, with respect to the spin direction, the angular motion of the missile on which the gyroscope is mounted. Some recent gyroscopes, such as fiber-optical gyroscopes and ring-laser gyroscopes, do not use a spinning rotor. They calculate the body rate by use of the Sagnac effect. Fiber-optical gyroscopes have an especially high specification with reasonable cost.
2. *Accelerometer.* The basic principle of operation of an accelerometer consists of the measurement of the inertial reaction force of a mass to an acceleration. The inertial reaction force of the mass causes a displacement of the mass, which is suspended in an elastic mounting system within the missile, and the acceleration of the missile can be read from the displacement of the suspended mass. Velocity and position information can be obtained by integrating the accelerometer signal. One must avoid placing the accelerometer near an antinode of the principal bending mode of the missile; otherwise, the vibration pick-up at this point may result in destruction of the missile.
3. *Altimeter.* The altimeter, which is an instrument used to measure altitude, is another sensor unit frequently employed in cruise missile systems. There are two common types of altimeters. A pressure altimeter, which is simply a mechanical aneroid barometer, gives an approximate altitude from which a more accurate value can be calculated; on the other hand, radio altimeters give absolute altitude directly. In radio altimeters, a transmitter radiates a frequency-modulated wave toward the earth, and the reflected signal is received on a separate antenna and combined with the signal taken directly from the transmitter. The frequency difference between the transmitted and the reflected signals indicates the height of the missile. Radio altimeters can be used to maintain automatically a missile at a preset altitude.

Controller Units

Controller units can be regarded as the "brain" of a missile, which tell a missile how to deflect the control surfaces or how to alter the thrust direction. The controller is in the form of preprogrammed logic and/or numerical operations installed in the on-board computer of a missile. There are two inputs to the controller units. One is from the sensor units, which provide the information about the actual motions of a missile, and the other input is from the guidance system, which provides the information about the commanded motions of a missile. The commanded motion and the actual motions are compared and manipulated in the controller units via a series of logic and/or numerical operations in order to output an intelligent decision, which renders the actual motions of a missile to match the commanded motions as closely as possible when fed into the actuator units. The series of operations involved in the controller unit is called control law. The most widely used control laws include amplification, integration, and differentiation of the error signal between the commanded motions and the actual motions.

1. *Amplification.* The amplification of error signal improves the robustness of the missile control system against uncertainties present in missile dynamics.
2. *Integration.* The integration of error signal effectively increases the closeness between the commanded motions and the actual motions.
3. *Differentiation.* The differentiation of error signal provides the trend of error propagation and decreases the required time for the actual motions to track the commanded motions.

With the increasing computation power of on-board computers, more advanced control laws can be implemented in the missile control loop to improve the agility of a missile. This point is addressed in more detail later.

Actuator Units

Actuator units are energy transformation devices. They receive the command from controller units and transfer it into enough power to operate control surfaces in order to direct the missile to the right heading. There are three methods of operating control surfaces: (1) by a pneumatic piston, (2) by a hydraulic piston, or (3) by an electric motor. The selection of actuating power depends on factors such as the speed, size, altitude, range, and weight of the missile.

1. *Pneumatic Actuator.* In a pneumatic system, air from a pressure source passes through suitable delivery tubes, valves, and pressure regulators to do work upon some mechanical units such as a piston or a diaphragm, which is connected to the missile control surfaces. Unlike a hydraulic system, a pneumatic system does not reuse its transfer medium after it has performed work on the load. For that reason, the air must be stored at a pressure much higher than that necessary for actuating the load. Therefore, a pneumatic system that depends on tanks of compressed air is obviously limited in range. The performance of a pneumatic system is also limited by the property of air compressibility. Because air is compressible, the movement of a pneumatic actuator is slow because of the time it takes to compress the air in the actuator to a pressure sufficient to move it.
2. *Hydraulic Actuator.* The operation of a hydraulic system is similar to the pneumatic system. The most prominent difference between the two systems is that the medium of transfer in the pneumatic system is a gas, whereas the medium of the transfer in the hydraulic system is a liquid. Hydraulic fluid is practically incompressible and will produce a faster reaction on an actuator, especially when the actuator must move against large forces. This asset is evidenced by the fact that large, high-speed missiles are controlled by hydraulic actuators. The main drawback of a hydraulic actuator is its weight and the maintenance problems. A hydraulic system normally weighs more because of the need for a pump, a reservoir, filters, and an accumulator. Also a hydraulic system is hard to maintain, requiring filling and bleeding operations.
3. *Electric Actuators.* Generally, motors are used as the actuators in the electrical energy transfer systems. Direct current (dc) motors develop higher stall torque than alternating current (ac) motors and, therefore, are used more often for driving heavy loads encountered in high-speed missile control. An ac motor is inherently a constant-speed device that is not suitable for the requirements of a servo motor where variation in rotation speed is necessary. This factor also makes the dc motor more applicable than the ac motor as an electric actuator in missile control. The use of all-electric missile control would simplify manufacture, assembly, and maintenance. Also, it would be easier to transmit information or power to all parts of the missile by wires rather than by hydraulic or pneumatic tubing. To enforce actuating efficiency, different methods of energy transfer (e.g., electropneumatic and electrohydraulic actuators) can be combined.

The preceding introduction describes the components and the operations of a missile control loop. A more detailed and fundamental introduction to the elements of missile control system can be found in Refs. 1 and 2. A missile's heading is changed by the action of actuators, which exert forces on control surfaces or on exhaust vanes. Altering missile heading by deflecting control surfaces is called aerodynamic control, whereas altering missile heading by deflecting exhaust vanes or by changing the jet direction is called thrust vector control. A control surface is not effective until the airflow across the surface has attained sufficient speed to develop a force. When missile speed is not high enough during the beginning of launch, the aerodynamic control is not effective, and its role is taken over by thrust vector control. The following two sections are dedicated to missile aerodynamic control and missile thrust vector control.

MISSILE AERODYNAMIC CONTROL

To control a missile accurately via aerodynamic forces, two general types of control surfaces (i.e., primary and secondary controls) are used. Primary control surfaces include ailerons, elevators, rudders, and canards; secondary control surfaces include tabs, spoilers, and slots. An understanding of missile aerodynamics is needed before a discussion of how these two groups of control surfaces work.

Missile Aerodynamics

Missile aerodynamics, like other flight vehicle aerodynamics, is basically an application of Bernoulli's theorem, which says that if the velocity of air over a surface is increased, the pressure exerted by the air on the surface must decrease, thus keeping the total energy constant. The top surface of a missile wing section has a greater curvature than the lower surface. The difference in curvature of the upper and lower surfaces builds up the lift force. Air flowing over the top surface of the wing must reach the trailing edge of the wing in the same time as the air flowing under the wing. To do this, air passing over the top surface must move at a greater velocity than air passing below the wing because of the greater distance the air must travel via the top surface. The increased velocity means a corresponding decrease of pressure on the surface according to the Bernoulli's theorem. Therefore, a pressure differential is created between the upper and lower surface of the wing, forcing the wing upward and giving it lift. Besides the wing, any other lifting surfaces and control surfaces of a missile exhibit exactly the same function.

The three-dimensional motion of a missile can be described in the body-axis coordinate system as shown in Fig. 2. The longitudinal line through the center of the fuselage is called the roll axis (x axis), the line that is perpendicular to the x axis and parallel to the wings is called the pitch axis (y axis), and the vertical line is considered as the yaw axis (z axis). The origin of the body-axis coordinate system (x, y, z) locates at the center of gravity. The three-dimensional missile motion can be resolved into two planar motions: pitch plane motion and yaw plane motion, where pitch plane is normal to the pitch axis, and yaw plane is normal to the yaw axis. The angle, measured in the pitch plane, between the projected missile velocity and the roll axis is called the angle of attack (AOA) denoted by α. The angle, measured in the yaw plane, between the projected missile velocity and the roll axis is called the angle of sideslip denoted by β. The resultant force on the wing or body can also be resolved into two components: the component in the pitch plane is called normal force, and

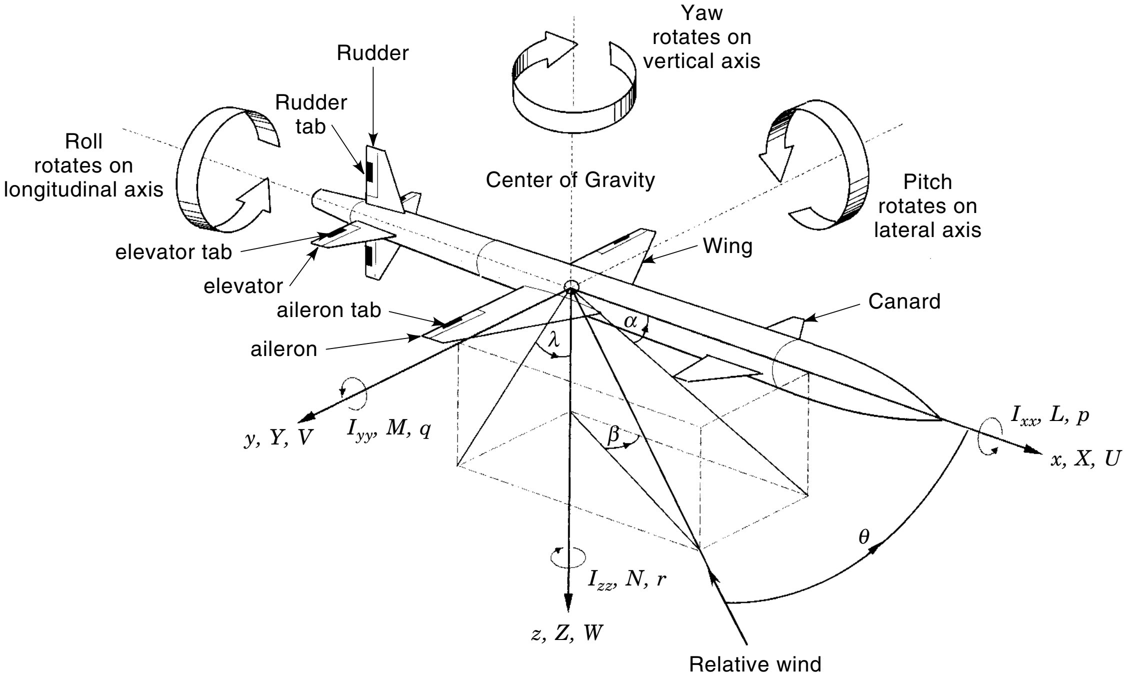

Figure 2. Schematic demonstration of the nomenclature used in missile dynamics. The locations of the primary control surfaces (rudder, elevator, aileron, and canard) and the secondary control surface (tabs) are shown. The definition of the roll, pitch, and yaw motions is also shown.

the component in the yaw plane is called side force. The normal force can be further resolved into two components: the component perpendicular to the projected missile velocity (in the pitch plane) is called lift and the component along the projected missile velocity is called drag. In many tactical missiles (e.g., short-range air-to-air missiles), the wing providing the lift force is not prepared. They keep a suitable AOA in the flight, where the lift force is produced by control fins or stability fins. Some fundamental control-related missile aerodynamics are surveyed in the following list. Readers who are interested in advanced missile aerodynamics can refer to Refs. 3 and 4 for details.

1. *Lift Force.* Lift force is the force by which aerodynamic control surfaces can change the attitude of a missile. Lift force depends on the contour of a wing, AOA, air density, area of the wing, and the square of the airspeed. The common equation for lift is given as

$$L = C_{\mathrm{L}}\frac{\rho}{2}AV^2 \tag{1}$$

   where L is the lift; C_{L} is the lift coefficient, which depends on the wing contour and the AOA; ρ is the air density; A is the area of the wing; and V is the airspeed. The lift coefficient C_{L} is determined by wind-tunnel tests and is plotted versus AOA as a characteristic curve for the particular airfoil. As the AOA increases, the lift coefficient increases linearly to a certain maximum value, which is the point where the air no longer flows evenly over the wing surface but tends to break away. This breaking away is called the stalling angle. After the stalling angle is reached, the lifting force is rapidly lost, as is the airspeed. For a fixed AOA, the lift coefficient C_{L} depends on the wing span and the profile of the wing. Increasing wing span or using the leading-edge slot or trailing-edge flap to increase the camber of wing profile may effectively increase the lift coefficient.

2. *Drag Force.* Drag is the resistance of air to forward motion and is an adverse factor of control effectiveness. It is the force that must be overcome by the thrust. The drag force in formula is

$$D = C_{\mathrm{D}}\frac{\rho}{2}AV^2 \tag{2}$$

   where C_{D} is the coefficient of drag obtained from characteristic curves of airfoils via wind-tunnel tests. For a small AOA, C_{D} changes very little with the AOA. As the AOA increases, C_{D} increases. The drag coefficient is usually quite small when compared with the lift coefficient. There are three sources of air drag. The skin friction of air on the wing is called profile drag; the air resistance of the parts of a missile that do not contribute to lift is called parasite drag; and the part of airfoil drag that contributes to lift is called induced drag. C_{L}, C_{D}, and other aerodynamic coefficients can be evaluated from empirical techniques, computational fluid dynamics (CFD) modeling, or by the processing of wind tunnel test data. It should be noted that various degrees of uncertainty are associated with each of these methods, with wind tunnel measurements usually being accepted as the most accurate.

3. *Wingtip Vortex.* The asymmetric wingtip vortex, which has a remarkable effect causing row-yaw instability at a high AOA, is always a challenge to missile control system design. As air flows about a wing, the pressure of

the air immediately above the upper surface is less than the air pressure immediately below the surface. With the air at a higher pressure below the wing, air will spill by the wingtips to the upper surface. This flow of air from the lower surface combines with the normal flow of air, causing a swirl of air at the wingtips. This swirl is called a wingtip vortex. At each side of the wingtip, the action of the vortex is to throw the air inward and downward. Induced drag is related to the downflow caused by the wingtip vortices.

4. *Downwash.* Because of the camber shape of the wing airfoil, air flow over the wing is deflected downward toward the elevator. This angle of deflection is called the downwash angle. When missile tail control is considered, the downwash effect caused by the wing must be seriously taken into account because downwash can significantly reduce the effective AOA of the tail surface and reduce the elevator ability of pitch control.
5. *Shock Wave Effect.* Shock wave is a prominent aerodynamic phenomenon when missile speed is at the transonic or supersonic ranges. As the speed of a missile increases, there comes a point at which the air can no longer get out of the way fast enough. The air tends to pile up or compress in front of the missile, setting up what is known as shock waves. In a shock wave, the pressure of air varies sharply, seriously altering the forces and pressure distribution on a missile. When shock waves are formed on the wings or control surfaces, the air flow across the shock waves tends to separate, causing drag to rise suddenly much as in a low-speed stall. At certain missile speeds, especially near the transonic range, the deflection of control surfaces may deteriorate the shock wave effect, which produces a peculiar vibration called flutter on control surfaces and can make control surfaces ineffective and even disintegrated.

Missile Stability

A stable missile can recover from the perturbed states spontaneously without control. Such stability is made possible by devices that stabilize a missile about its three axes. Accordingly, these devices are called stabilizers. The simplest stabilizer is the feathered fins at the rear of an arrow because it provides for a stable line of flight. Three types of stabilizers are required to stabilize a missile about its three axes.

1. *Pitch Stabilizer.* Missile stability about the lateral (pitch) axis is achieved by a horizontal surface at the tail of the missile. This horizonal surface consists of two parts: the stationary part as the pitch stabilizer and the movable part as the elevator. The degree of pitch stability can be quantitatively expressed by an index called static margin, which is the distance of the center of pressure (c.p.) to the center of gravity (c.g.). The c.p. is the point through which the combined aerodynamic forces caused by body, wings, and control surfaces are acting. If c.p. is behind the c.g. (i.e., the static margin is positive), the missile is said to be statically stable. In this case, any perturbation of the body away from the direction of the velocity vector results in a moment about the c.g. that tends to decrease this perturbation. This of course is the reason why feathers are placed at the rear end of an arrow to move the c.p. aft. If a missile has no autopilot (i.e., no instrument feedback), a sizable static margin, say 5% or more of the overall length, has to be allowed to ensure stability. However, if the static margin is excessively positive, the missile is unnecessarily stable, and control moments will be relatively ineffective in producing a sizable maneuver. On the other hand, although a missile with negative static margin is statically unstable, it may exhibit great agility when autopilot is installed. It is worth noting that the static margin of a missile is not a fixed value, because of the c.p. variation for different flight conditions and the c.g. variation caused by propellant usage. A challenging missile control problem is to ensure the stability of the airframe for all possible c.p. and c.g. locations.
2. *Yaw Stabilizer.* Missile stability about the vertical (yaw) axis is usually provided for by a vertical fin. If a missile tends to turn to the left, the pressure on the right side of the fin is increased. This increased pressure resists the rotation and forces the tail in the opposite direction. In some missiles, the fin may be divided and have a movable part called the rudder that is used for directional control. Besides the fin, the vertical sides of the fuselage also act as stabilizing surfaces. Another way to increase the yaw stability is via sweepback of wings.
3. *Row Stabilizer.* Missile stability about the longitudinal (row) axis is achieved by a dihedral and by the positioning of the wing. A dihedral angle is the angle formed by a reference line through the wing surface and the lateral axis of the missile. Dihedral produces stability by causing a change of lift on the wing surfaces. As a missile starts to roll, it will sideslip slightly and thus create a relative wind component. This component increases the lift on the lower wing and decreases the lift on the higher wing. Hence, an opposite torque is generated to stop rowing. The positioning of the wings at the time a missile is constructed is another means of obtaining stability about the row axis. A missile has greater row stability if the wings are placed above the center of gravity than if they are placed below the center of gravity.

Primary Control Surfaces

Ailerons, rudders, elevators, canards, and their various combinations are considered primary controls. These control surfaces are shown schematically in Fig. 2. As these control surfaces are deflected, they present a surface to the existing air flow at an angle that will cause a force to exist. This force pushing against the control surface moves the wing or tail to which the control surface is attached in a direction opposite to the control surface movement.

1. *Ailerons.* A conventional aileron is attached to the outer trailing edge of the wings to control the missile row motion in a manner that when one aileron is lowered, the opposite one is raised.
2. *Elevators.* Elevators are attached to the pitch stabilizer on the tail to control pitch motion. They are raised and lowered together.

3. *Rudders.* A rudder is attached to the rear part of the vertical stabilizer and is used to maintain directional (yaw) control.
4. *Canards.* A canard is basically a forward wing located ahead of the center of gravity of the missile for the purposes of stabilization and pitch control. One type of canard structure consists of a fixed stabilizing plane with a surface control attached to the trailing edge. Another type of canard structure uses a pivoted mechanism that allows the entire stabilizing plane to rotate up or down.
5. *Dual-Purpose Control Surfaces.* The preceding control surfaces can be properly combined to give multipurpose control functions. Feasible combinations include elevons, ailevators, and rudder-vators. As the names indicate, they consist of control surfaces that accomplish two purposes. For instance, an elevon takes the place of an elevator and an aileron, giving control of pitch and roll.
6. *Variable-Incidence Control Surfaces.* This type of control rotates the position of an entire wing rather than just part of it. The variable incidence control can overcome the problem of flutter and the need for structural strength of control surfaces and yet have a control that is sensitive and effective at various speed ranges. The variable incidence control can be used on the wing, horizonal stabilizer, or vertical stabilizer.

Secondary Control Surfaces

Primary control surfaces can be looked upon as the main controlling factor of the missile's path; however, by using secondary control surfaces, a missile can be controlled much more accurately and efficiently. A secondary group of aerodynamic control surfaces is composed of tabs, slots, and spoilers, which are schematically demonstrated in Fig. 2. For the convenience of compact illustration, all six primary control surfaces and the three secondary control surfaces are put together in one missile, as shown in Fig. 2; however, a missile may not be equipped with all types of primary and secondary control surfaces. For example, missiles in general do not have both tail and canard controls, and conventional missiles do not have secondary control surfaces, which are almost exclusively used in large cruise missiles.

1. *Tabs.* Tabs are small pieces of movable or fixed metal attached to the trailing edge of the primary control surfaces. They help to trim the missile or to alleviate the loading of the primary control surfaces, but they do not in themselves determine the direction of missile motion. Tabs can be divided into three types: fixed, trim, and booster. A fixed tab can be bent uniformly in the required direction to trim the missile. A trim tab is movable and controllable, and is used to trim the missile with varying attitude, speed, or altitude. A booster tab, sometimes known as a servo tab, is used to assist in moving primary control surfaces with large area.
2. *Slots.* A slot is a high-lift device located along the leading edge of the wing. The slot is ineffective in the region of a normal AOA, but when a missile reaches a high AOA, the slot can be opened to allow air to spill through and hence delay the formation of turbulence flow over the top surface of the wing.
3. *Spoilers.* As the name indicates, a spoiler is used to generate turbulence flow and "spoil" the lift on a wing. When not used, spoilers are recessed into the upper camber of the wings and allow the flow of air over the wing to be smooth and uninterrupted. If, however, a gust of wind has caused the right wing to drop, the control system instantly calls for the spoiler on the left wing to extend. As the spoiler extends, the lift on the left wing is spoiled and reduced a considerable amount. The wings then tend to return to the original position.

MISSILE THRUST VECTOR CONTROL

A completely different method of steering a missile is to alter the direction of the efflux from the propulsion motor. This method is known as thrust vector control (TVC). TVC is clearly not dependent on the dynamic pressure of the atmosphere and is generally used in the phase of flight where missile speed is so low that the airfoil sections do not have enough aerodynamic stabilizing effect. On the other hand, TVC is inoperative after propulsion motor burn-out, but at this time aerodynamic forces become large enough to take over the role of TVC. There are several methods of directing the thrust of a rocket motor, and each has advantages and disadvantages, which may or may not recommend it for a particular application. References 1 and 5 provide more information on TVC.

1. *Exhaust Vanes.* Exhaust vanes are surfaces that are installed directly in the exhaust path of the jet engine. When the position of the vane is changed, it deflects the exhaust and causes the thrust to be directed in opposition to the exhaust vane. The operation of exhaust vanes is sketched in the middle part of Fig. 3. Because of the severe erosion problem caused by the tremendous heat in the exhaust, the life of exhaust vanes is generally short. Graphite and more recently tungsten and molybdenum have been used as the materials of the exhaust vanes. To reduce the complexity of the actuator design, the actuating mechanism of an exhaust vane often shares with that of aerodynamic control surfaces; therefore, when control surfaces move in the ambient air path, an exhaust vane moves, simultaneously and with the exact same manner, within the exhaust path of the jet engine. The device "jetavators" is the outcome of such a design idea, which can control jet and elevator simultaneously. Perhaps the oldest TVC is the exhaust vane used in the German V2 in World War II. Many surface-to-surface missiles, including the American Pershing, have used exhaust vanes to control the jet direction.
2. *Gimbaled Engine.* By mounting the combustion chambers in gimbals and controlling its position by servos, the direction of thrust can be altered. The operation of gimbaled engine is sketched in the lower part of Fig. 3. Two serious objections to this method are that all the various fuel lines must be made flexible, and the servo system that actuates the jet must be extremely strong. However, gimbaled liquid-propellant engines have been used successfully for many years. For example, the Viking research vehicles have been successfully flown many

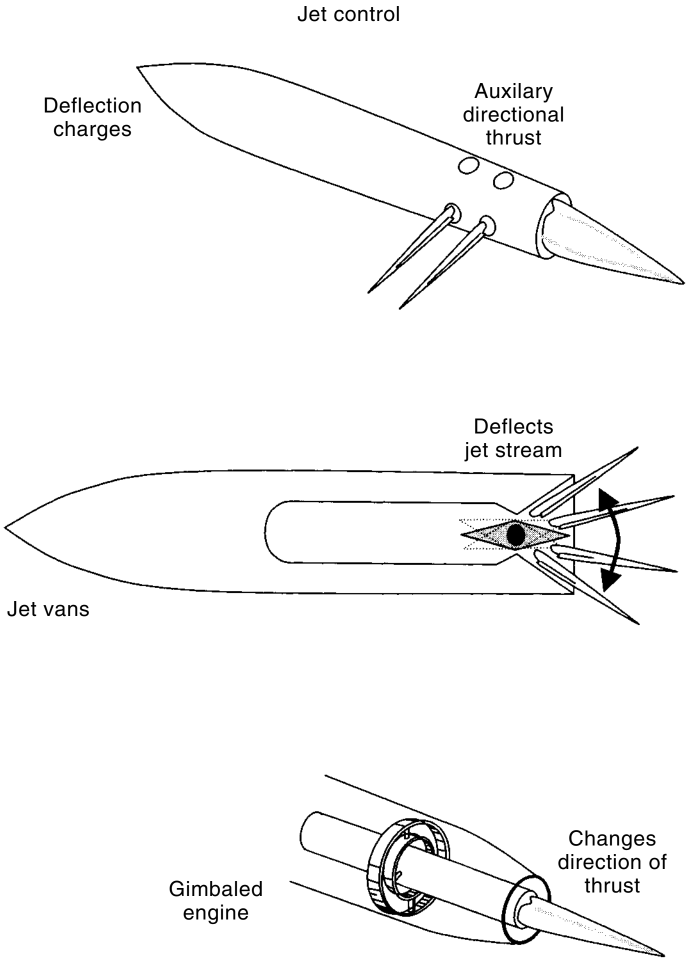

Figure 3. Three thrust vector control methods. The upper part sketches the operation of reaction control thruster; the middle part sketches the operation of exhaust vane; and the lower part sketches the operation of gimbaled engine.

times using this type of control during phases of flight wherein aerodynamic control is inadequate.

3. *Moving Nozzles.* Instead of moving the entire combustion chamber, we can also alter the direction of thrust by changing the orientation of the nozzle. This can be accomplished by using a flexible nozzle or a ball-and-socket nozzle. A flexible nozzle is formed by attaching the nozzle to the motor case by means of a flexible rubber mounting that is very stiff axially but relatively compliant in the pitch and yaw planes. Thrust deflection of 4° to 5° is feasible by this method, but a large resistance to movement is encountered when an increasingly larger deflection angle is required. Another way of attaching the nozzle to the propulsion motor is via a ball-and-socket joint with some form of low-friction seal. Although there will be some coulomb friction in this type of connection, the actuation torque will not increase with the deflection angle.
4. *Injection Method.* By injecting a liquid or gas into the motor venturi, we can obtain a sideways component of resultant thrust. The maximum jet deflection by using inert liquid as the injection fluid was found to be 4°. Jet deflection of up to 12° has been obtained by injecting hot gas bled directly from the combustion chamber.
5. *Reaction Control Thruster.* An easier system of jet control is accomplished by placing several small thrusters at various points about the missile body. Control is accomplished by using one or another of these jets as desired, thus giving different directions of thrust. The operation of reaction control thruster is sketched in the upper part of Fig. 3. This method eliminates the use of the outside control surfaces, affording a cleaner missile surface. When reaction control thrusters are used, there will be an interaction of the jet plume with the free stream flow. This jet interaction is very nonlinear with the AOA and dominates the effective moment produced by the reaction thrusters. The produced moment may be larger or smaller than the jet thrust force times its moment arm, depending on the height by which the jet penetrates into the free stream. Reference 6 discusses missile attitude control using reaction control thruster.
6. *Jet-Driving Control Surfaces.* This method employs jet or air injection over aerodynamic surfaces for actuating augmentation.

MISSILE CONTROL CONFIGURATION

According to the aforementioned various missile control methodologies, we can now give a classification of missile configuration with respect to the location of controls. If the controls are located well behind the center of gravity of the missile, the term *tail control* applies. If the controls are placed forward of the center of gravity, the term *canard control* applies. When the control is mounted on the main lifting surface near the center of gravity, the term *wing control* applies. What type of control surface to be used depends on the type of missile configuration in question. Regarding missile configuration, Refs. 1, 5, and 7 serve as good references.

Wing-Control Configuration

A wing-control configuration consists of a relatively large all-moving wing located close to the center of gravity of the missile and a set of tail or stabilizing surfaces at the aft end of missile. This all-moving wing serves as an aforementioned variable-incidence control surface. This type of control is used mostly in an air-to-air missile because of its extremely fast response characteristics. If the right and left moving wings are controlled by separate servos, they can be used as ailerons and elevators; the word *elevons* as mentioned earlier is applied to such a dual-purpose control surface. There are two main advantages in using wing-control configuration:

- *Air Inlet Consideration.* Instantaneous lift can be developed as a result of wing deflection via a pivoted mechanism with little increase of missile AOA. This low value of AOA is advantageous particularly from the standpoints of inlet design for air-breathing power-plant and guidance-seeker design. For example, if the propulsion system is a ram jet, the air inlet is likely to choke if the body AOA is large, say 15° or more. The use of wing control can greatly reduce the chance of inlet choke and maintain the engine efficiency by keeping the body AOA to a minimum. This point will be further addressed in the later sections.

- *Servo Location Consideration.* The servos used in wing-control configuration are located near the center of the missile body. There are some occasions when the servos are most conveniently placed near the center of the missile. For example, if a medium-range missile has two separate motors, a boost motor and a sustain motor, the former may occupy the whole of the rear end of the missile and the sustainer motor may occupy most of the remaining rear half of the body. In such a case, there is just no room to install servos at the rear. If the missile carries a homing head, the servos cannot be placed at the front either.

However, there are some distinct penalties involved in the use of wing control.

- Pitch control effectiveness from the wings is generally very low as a result of short pitching moment arm because the lift developed is located close to the center of gravity of the missile.
- Large aerodynamic hinge moments are required because of the large wing area.
- Relatively large loss will be induced in tail effectiveness as a result of downwash.
- Nonlinear aerodynamics is resulted from downwash caused by both wing deflection and AOA.
- Severe adverse rolling moments is induced on the tail surfaces from combined effects of AOA and wing deflection.

Canard-Control Configuration

A canard-control configuration consists of a set of small control surfaces called canards located well forward on the body and a set of large surfaces (wing or tail) attached to the middle or aft section of the missile. Its advantages and disadvantages follow.

Advantages. Advantages of canards include the following:

- Canards, because of their small size, do not generate a significant amount of downwash to affect the longitudinal stability adversely. Thus relatively large static-stability margins can easily be obtained by simple changes in wing location.
- Canard configuration has the inherent simplicity of packaging because the control system is small.

Disadvantages. Disadvantages include the following:

- Roll stabilization is difficult when the canard surface is used because of their size and downwash effect on the wings. Usually a separate set of lateral controls such as wing-tip ailerons is needed for canard configuration.
- Relative high control-surface rates are required to obtain the desired rate of response because AOA must be generated before any lift is developed.

Tail Control Configuration

Many missiles employ tail control for its convenient packaging. Usually it is desirable to have the propulsion system placed centrally in the missile so that the center of gravity movement caused by propellant usage is minimized. It is convenient and sometimes essential to have the warhead and fuse at the front together with any associated electronics including the guidance receiver. This leaves the control system to occupy the rear end with the propulsion blast pipe passing through its center.

Advantages. Advantages of tail control include the following:

- The tail loads and hinge moments can be kept relatively low as the total AOA on the tail is reduced.
- The wing-tail interference effects are reduced because the forward main lifting surface is fixed (i.e., no downwash caused by wing deflection). Therefore, the aerodynamic characteristics are more linear than those for wing-control design.

Disadvantages. Disadvantages include the following:

- With this type of control, it is obvious that the tail deflection must be opposite in direction to the AOA. This feature results in relatively slow response characteristics because the initial lift is in a direction opposite to the desired one.
- Deficiency of tail surfaces to provide the desired lateral control.

Wing Arrangements

Wing arrangements have a significant influence on the types of missile control to be used. Three types of wing arrangements are discussed here.

1. *Cruciform.* The most commonly used configuration in missile design is the cruciform, which possesses four wing surfaces and four tail surfaces. There are several major advantages in the use of this type of configuration: (i) fast response in producing lift in any direction, (ii) identical pitch and yaw characteristics, and (iii) simpler control system as the result of item (ii). One of the most important aspects associated with a cruciform design is the orientation of the tail surface with respect to the wing planes. The significant conclusion from considerable experience and experimental data was that an in-line tail surface (i.e., all the four tail surfaces are in the same orientations as the four wing surfaces) provides the best overall aerodynamic characteristics for most missile applications. The other possible wing-tail geometrical relation is called interdigitated configuration where there is a 45° separation between the wing and tail orientation. For a cruciform missile, the most difficult parameter to determine accurately is the induced rolling moment. The rolling moments arise whenever the missile simultaneously executes pitch and yaw maneuvers that are unequal in magnitude. Such maneuvers result in unequal or asymmetric flow patterns

over the aerodynamic lifting surface; consequently, rolling moments are induced on the airframe. Hence, roll stabilization or control is a critical issue for cruciform missiles.

2. *Monowing.* The monowing arrangements are generally used on cruise-type missile (i.e., missiles design to cruise for relatively a long range like crewed aircraft). This type of design is generally lighter and has less drag than the cruciform configuration. The wing area and span are, however, somewhat larger. Although the monowing missile must bank to orient its lift vector in the desired direction during maneuvering flights, the response time may be sufficiently fast and acceptable from a guidance-accuracy standpoint. The induced-roll problem for the monowing configuration is substantially less severe than that associated with the cruciform configuration. A separate set of lateral control surfaces, such as flaps, spoilers, and wing-tip ailerons, is generally used in a monowing design. This stems from the fact that the canard or tail surfaces that are usually employed for pitch control on monowing design are generally inadequate for lateral control.
3. *Triform.* This type of wing arrangement, which employs three wings of equal area spaced 120° apart, is seldom used because no noticeable advantage can be realized. Results of a brief preliminary analysis indicate that the total wing area of the triform is equal to that used on a cruciform arrangement and that consequently no noticeable change in drag may be realized. In addition, little or no weight saving will be realized, even though one less arrangement or fitting is required because the total load remains the same.

MISSILE CONTROL STRATEGY

Because the missile control system (autopilot) is commanded by the missile guidance system, the autopilot command structure is dependent on guidance requirements for various mission phases.

- *Separation (Launch) Phase.* A body rate command system is typically used during launch because of its robustness to the uncertain aerodynamics.
- *Agile Turn.* During an agile turn, directional control of the missile's velocity vector relative to the missile body is desired. This amounts to commanding AOA or sideslip, and regulating roll to zero.
- *Midcourse and Terminal Phases.* An acceleration command autopilot is commonly employed in these two phases.
- *End of Homing Phase.* At the end of terminal homing, the missile attitude may be commanded to improve the lethality of the warhead.

Among these four autopilot structures, separation, midcourse, and endgame autopilots are in general well understood and have been implemented in production missiles. Autopilot designs for agile turns are significantly less well understood. Reference 8 gives a detailed discussion of the challenges involved in agile turn, and several solution techniques were provided there.

Up to now, the existing missile control strategies in various mission phases include two major categories: skid-to-turn (STT) strategy and bank-to-turn (BTT) strategy. It is interesting to note that the progress in control strategy for crewed aircraft is from BTT to direct sideslip control (i.e., STT), whereas the progress in missile control strategy is from STT to BTT. The applications and limitations of STT and BTT will be introduced in the following sections.

Skid-to-Turn Strategy

In STT the missile roll angle may be either held constant or uncontrolled; in either case, the magnitude and orientation of the body acceleration vector is achieved by permitting the missile to develop both an AOA and a sideslip angle. The presence of the sideslip imparts a "skidding" motion to the missile; hence the name skid-to-turn. The STT missile autopilot receives the guidance command interpreted in terms of the Cartesian system. In the Cartesian system, the missile-guidance system produces two signals, a left–right signal and an up–down signal, which are transmitted to the missile-control system by a wire or radio link to rudder servos and elevator servos, respectively. If a cruciform missile adopts STT control strategy, the two servo channels can be made identical because of the identical pitch and yaw characteristics of a cruciform missile as mentioned earlier. Hence, in STT missiles, both pitch control and yaw control are called lateral control, which is different from the definition of aircraft control.

The other control loop of the STT missile is roll control, which is used to stabilize the missile roll position. For a perfect performance of the STT missile, it is assumed that the missile will remain in the same roll orientation as at launch during the whole flight. In this ideal case, up–down signals, if sent to the elevator servos, should then result in a vertical maneuver only; and left–right signals, if sent to the rudder servos, should result in a horizontal maneuver only. However, a missile, except for a monowing missile, is not designed like an airplane and there is no tendency to remain in the same roll orientation. In fact, it will tend to roll for many reasons such as accidental rigging errors, asymmetrical aerodynamic loadings, and atmospheric disturbances. Two methods ensure that left–right commands are performed by rudder servos and up–down commands are performed by elevators. The first method applies a quick roll servo (with bandwidth larger than that of lateral servos) to stabilize the roll dynamics and to recover the missile to the original roll orientation. The second method allows the missile to roll freely but installs a roll gyro and resolver in the missile to ensure that the commands are mixed in the correct proportions to the elevators and rudders.

However, roll stabilization (the first method) is generally more preferred for the following reasons:

- There are many occasions when roll position control is necessary, for example, to ensure that the warhead or altimeter always points downward.
- If the missile is free to roll, high roll rates may cause cross-coupling between the pitch and yaw channels and tend to unstabilize the system.

An STT missile with properly controlled roll motion may provide the following advantages:

- Same degree of vertical and horizontal maneuverability can be achieved.

- With STT control it is possible to resolve three-dimensional target and missile motion into two independent planar motions and to consider the pitch and yaw channels as an independent two-dimensional problem. Hence, both guidance law and control system design can be done via two-dimensional analysis. This simplification makes it possible to apply the classic control theory, which treats single-input single-out (SISO) system to the missile autopilot design.

Bank-to-Turn Strategy

The concept of BTT stems from the motion of crewed aircrafts, which use ailerons to bank (roll) to the left or right. During a left or right turn, a small amount of rudder is also applied in an attempt to make the air flow directly along the longitudinal axis of the aircraft. Hence, in BTT motion, there is no sideslip and no net side force. From a passenger's point of view, this method of maneuvering is the most comfortable because the total force experienced is always symmetrically through the seat. When BTT concept is applied to missile control, the missile is rolled first so that the plane of maximum aerodynamic normal force is oriented to the desired direction and the magnitude of the normal force is then controlled by adjusting the pitch attitude (AOA). If we consider the guidance command for an STT missile as being expressed in the Cartesian coordinates (x, y) where x is the right–left command and y is the up–down command, then the guidance command for a BTT missile can be considered as being expressed in the polar coordinates (r, ϕ) where ϕ is the angle to roll and r is the distance to be steered in the pitch plane. Therefore,BTT strategy is sometimes called polar control or "twist-and-steer" control.

Although BTT control has been used in crewed aircraft for a long time, the interest in BTT missile control only began in the late 1970s. The principle motivation for developing the BTT missile autopilot stems from the successful application of ramjet propulsion technology to missile system. Several ramjet missiles were developed in the late 1970s, including ramjet interlab air-to-air technology (RIAAT program, Hughes), advanced common intercept missile demonstration (ACIMD program, Naval Weapons Center), advanced strategic air-launched multi-mission missile (ASALM program, McDonnell Douglas and Martin-Marietta). These BTT programs are thoroughly surveyed in Ref. 9. All these ramjet missile programs require autopilot to prevent missile maneuvers from shading the inlet (i.e., the AOA needs to be small and positive) and to limit sideslip β in order to increase engine efficiency and thereby maximize range. The conventional STT strategy cannot satisfy these limitations on α and β. The applicability of the ramjet missile requires investigation in the following areas:

1. *Monowing Configuration.* Ramjet missiles have two inlets external to the main body and there is room for only one pair of wings (i.e., monowing).
2. *Variable-Incidence Wing Control.* Because the inlets could accept only a small AOA as a result of interference from the body, the use of variable-incidence wing control, which can provide instantaneous lift without increasing the AOA of the body, is very suitable for ramjet engines.
3. *BTT Autopilot Design.* If a ramjet missile has two fixed wings and is controlled with four cruciform tails, the best solution is to adopt a BTT autopilot, which can ensure small values of AOA and sideslip angle.

Only the technique in item 3 is discussed here. The design of a highly maneuverable BTT autopilot poses a severe challenge to the control designer. High maneuverability means not only high aerodynamic acceleration but also the ability to change the orientation of the acceleration rapidly. This means that the roll rate can be expected to be much larger (perhaps by an order of magnitude) than they would be in a STT missile. The large roll rates induce substantial cross-coupling between the pitch and the yaw axes, whereas in a typical STT missile this cross-coupling is negligible. The main advantage of BTT strategy is its adaptability to ramjet missile control, but there are many difficulties that cannot be conquered by the techniques used in STT strategy:

- The cross-coupling between the pitch and yaw axes requires the designer to consider both axes together as a single multi-input/multi-output (MIMO) system. The classic SISO control approach becomes inadequate for BTT application, and modern MIMO control theory needs to be considered.
- The cross-axes couplings are proportional to the roll rate, which is a dynamic variable. This means that the dynamics of the pitch and yaw axes are not only cross-coupled but also nonlinear. Therefore, a single fixed-coefficient linear autopilot may be unable to cover the whole flight envelope, and linear autopilot with gain scheduling or nonlinear autopilot design should be taken into account.
- The three-dimensional motion of a BTT missile cannot be resolved into two planar motions. Hence, the guidance law design for a BTT missile needs detailed three-dimensional analysis.

In summary, a BTT missile can be considered as a MIMO system with nonlinear dynamics and with three-dimensional kinematics, whereas a STT missile can be well approximated as an integration of three SISO systems with linear dynamics and with two-dimensional kinematics. Reference 8 summarizes some status and concerns of BTT missiles. How modern control theory can be used to design BTT autopilots is discussed in Ref. 10.

MISSILE AUTOPILOT DESIGN

Equations of Motion

The equations of motion of a missile with controls fixed may be derived from the Newton's second law of motion, which states that the rate of change of linear momentum of a body is proportional to the summation of forces applied to the body and that the rate of change of the angular momentum is proportional to the summation of moments applied to the body. Mathematically, this law of motion may be written as

$$\frac{d}{dt}\begin{bmatrix} mU \\ mV \\ mW \end{bmatrix} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}, \quad \frac{d}{dt}\begin{bmatrix} H_x \\ H_y \\ H_z \end{bmatrix} = \begin{bmatrix} L \\ M \\ N \end{bmatrix} \tag{3}$$

where (X, Y, Z) and (L, M, N) are the resultant forces and moments caused by aerodynamic forces, gravity, and propulsive forces, along the body axes (x, y, z). (U, V, W) and (H_x, H_y, H_z) are the components of the velocity and angular momentum of the missile about the x, y, and z axes, respectively. The two main reasons for the use of body axes in the dynamic analysis of the missile are (1) the velocity along these axes are identical to those measured by instruments mounted in the missile and (2) the moments of inertia (i.e., I_{xx}, I_{xy}, etc.) are independent of time. Equation (3) and (4) can be expressed in terms of the moments of inertia and the missile angular velocity P, Q, and R as follows:

$$m\begin{bmatrix}\dot{U}+QW-RV\\ \dot{V}+RU-PW\\ \dot{W}+PV-QU\end{bmatrix}=\begin{bmatrix}X\\ Y\\ Z\end{bmatrix} \tag{4a}$$

$$\begin{bmatrix}I_{xx} & -I_{xy} & -I_{xz}\\ -I_{xy} & I_{yy} & -I_{yz}\\ -I_{xz} & -I_{yz} & I_{zz}\end{bmatrix}\begin{bmatrix}\dot{P}\\ \dot{Q}\\ \dot{R}\end{bmatrix}+\begin{bmatrix}0 & -R & Q\\ R & 0 & -P\\ -Q & P & 0\end{bmatrix}\begin{bmatrix}I_{xx} & -I_{xy} & -I_{xz}\\ -I_{xy} & I_{yy} & -I_{yz}\\ -I_{xz} & -I_{yz} & I_{zz}\end{bmatrix}\begin{bmatrix}P\\ Q\\ R\end{bmatrix}=\begin{bmatrix}L\\ M\\ N\end{bmatrix} \tag{4b}$$

For a missile with monowing configuration, the xz plane is a plane of symmetry. Consequently, $I_{yz} = I_{xy} = 0$ from the definition of moment of inertia. Hence, Eqs. (4) may be simplified as follows:

$$m(\dot{U}+QW-RV)=X \tag{5a}$$

$$m(\dot{V}+RU-PW)=Y \tag{5b}$$

$$m(\dot{W}+PV-QU)=Z \tag{5c}$$

$$\dot{P}I_{xx}+QR(I_{zz}-I_{yy})-I_{xz}(\dot{R}+PQ)=L \tag{5d}$$

$$\dot{Q}I_{yy}+PR(I_{xx}-I_{zz})+I_{xz}(P^2-R^2)=M \tag{5e}$$

$$\dot{R}I_{zz}+PQ(I_{yy}-I_{xx})-I_{xz}(\dot{P}-QR)=N \tag{5f}$$

These differential equations govern the motion of a monowing missile with BTT control. It can be seen that these equations are nonlinear and cross-coupled; none of the equations can be isolated from the others. Taking Eq. (5b) as an example, the term $-mPW$ says that there is a force in the y direction caused by the incidence in pitch (i.e., $\alpha = W/U$) and the roll motion P. In other words, the pitching motion (W) of the missile is coupled to the yawing motion (Y force) on account of roll rate P. Equation (5a) does not really concern us because, in most cases, we are interested in the acceleration normal to the velocity vector as this will result in a change in the velocity direction. In any case, in order to determine the change in the forward speed U, we need to know the magnitude of the propulsive and drag force. Nevertheless, except for power phase, the variation of U is generally very small.

For a missile with cruciform configuration, further simplifications can be made because (1) the xy plane (as well as xz) is also a plane of symmetry (i.e., $I_{xz} = 0$) and (2) the moment of inertia about the y axis is generally equal to that about the z axis (i.e., $I_{yy} \approx I_{zz}$). Hence, the resulting equations become

$$m(\dot{U}+QW-RV)=X \tag{6a}$$

$$m(\dot{V}+RU-PW)=Y \tag{6b}$$

$$m(\dot{W}+PV-QU)=Z \tag{6c}$$

$$\dot{P}I_{xx}=L \tag{6d}$$

$$\dot{Q}I_{yy}+PR(I_{xx}-I_{zz})=M \tag{6e}$$

$$\dot{R}I_{zz}+PQ(I_{yy}-I_{xx})=N \tag{6f}$$

These are the general equations used in the analysis of STT control strategy, especially for agile STT missiles with substantial induced roll. When rolling rate P is relatively small when compared with Q and R, further simplification of Eq. (6) is possible by dropping the terms relating to P, and the result is the three decoupled servo channels used in the conventional STT autopilots.

1. Pitch dynamics:

$$m(\dot{W}-QU_0)=Z,\quad I_{yy}\dot{Q}=M \tag{7a}$$

2. Yaw dynamics:

$$m(\dot{V}+RU_0)=Y,\quad I_{zz}\dot{R}=N \tag{7b}$$

3. Roll dynamics:

$$I_{xx}\dot{P}=L \tag{7c}$$

where the forward speed U is assumed to be a constant U_0 because $\dot{U}$ is generally small. It can be observed that each servo channel is decoupled, linear, and SISO (i.e., each channel has a single input and a single output: the pitch dynamics with elevator input and AOA [$\alpha(t) = W(t)/U_0$] output, the yaw dynamics with rudder input and sideslip [$\beta(t) = V(t)/U_0$] output, and the roll dynamics with aileron input and roll rate P output). This formulation is rather simplified, but very promising results had been recognized in an STT autopilot application.

In general, the resultant forces X, Y, Z, and moments L, M, N in Eq. (6) are nonlinear functions of U, V, W, P, Q, R, and of the control surface deflections. However, a linear control system is designed under the condition that the missile is exercised through small perturbations about some trim conditions (equilibrium conditions). From the viewpoint of autopilot design, a linear Taylor expansion of the resultant forces and moments about the trim conditions is adequate. We will use the symbol with subscript zero (0) to stand for trim condition and the symbol with a lowercase letter to denote the perturbation quantities. For example, V is expressed by $V(t) = V_0 + v(t)$ where V_0 is the steady-state side speed and v is the perturbed side speed which is a function of time. The other variables can be expressed in the same way. The deflection angles of aileron, elevator, and rudder, will be denoted by δ_a, δ_e, and δ_r, respectively.

Forces and moments can also be expanded in a perturbed form. For example, assume that the side force $Y(V, R, \delta_r)$ is a function of V, R, and δ_r. It can be expanded as

$$\begin{aligned} Y(V, R, \delta_\mathrm{r}) &= Y(V_0, R_0, \delta_{r_0}) + \frac{\partial Y}{\partial v} v + \frac{\partial Y}{\partial r} r + \frac{\partial Y}{\partial \delta_\mathrm{r}} \delta_\mathrm{r} \\ &= Y_0 + y_\mathrm{v} v + y_\mathrm{r} r + y_{\delta_\mathrm{r}} \delta_\mathrm{r} \end{aligned} \tag{8}$$

where Y_0 is the steady-state side force; $y_\mathrm{v} = (\partial Y/\partial v\ (V_0, R_0, \delta_{r_0})$, $y_\mathrm{r} = (\partial Y/\partial r)\ (V_0, R_0, \delta_{r_0})$, $y_{\delta_\mathrm{r}} = (\partial Y/\partial \delta_\mathrm{r})\ (V_0, R_0, \delta_{r_0})$ are called aerodynamic derivatives evaluated at the specified trim condition. Aerodynamic derivatives with respect to state variables are also called stability coefficients such as y_v, and y_r; derivatives with respect to control surface deflection are also called control coefficients such as y_{δ_r}. Remaining forces and moments can be linearized in a similar way as in Eq. (8). Substituting these linearized quantities into Eq. (7) yields the control equations for a STT missile as

1. Pitch dynamics:

$$\begin{bmatrix} \dot{w} \\ \dot{q} \end{bmatrix} = \begin{bmatrix} z_\mathrm{w} & U_0 + z_\mathrm{q} \\ m_\mathrm{w} & m_\mathrm{q} \end{bmatrix} \begin{bmatrix} w \\ q \end{bmatrix} + \begin{bmatrix} z_{\delta_\mathrm{e}} \\ m_{\delta_\mathrm{e}} \end{bmatrix} \delta_\mathrm{e} \tag{9}$$

2. Yaw dynamics:

$$\begin{bmatrix} \dot{v} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} y_\mathrm{v} & -U_0 + y_\mathrm{r} \\ n_\mathrm{v} & n_\mathrm{r} \end{bmatrix} \begin{bmatrix} v \\ r \end{bmatrix} + \begin{bmatrix} y_{\delta_\mathrm{r}} \\ n_{\delta_\mathrm{r}} \end{bmatrix} \delta_\mathrm{r} \tag{10}$$

3. Roll dynamics:

$$\dot{p} = l_\mathrm{p} p + l_{\delta_\mathrm{a}} \delta_\mathrm{a} \tag{11}$$

The Laplace transfer function from the aileron input δ_a to the roll rate output can be found from Eq. (11) as

$$\frac{p}{\delta_\mathrm{a}} = \frac{-l_{\delta_\mathrm{a}}/l_\mathrm{p}}{T_\mathrm{a} s + 1} \tag{12}$$

where $-l_{\delta_\mathrm{a}}/l_\mathrm{p}$ can be regarded as the steady state gain and $T_\mathrm{a} = -1/l_\mathrm{p}$ can be regarded as the time constant of the roll channel. The Laplace transfer function from the rudder input δ_r to the body yaw rate r can be obtained from Eq. (10) as

$$\frac{r}{\delta_\mathrm{r}} = \frac{n_{\delta_\mathrm{r}} s - n_{\delta_\mathrm{r}} + n_\mathrm{v} y_{\delta_\mathrm{r}}}{s^2 - (y_\mathrm{v} + n_\mathrm{r})s + y_\mathrm{v} n_\mathrm{r} + U_0 n_\mathrm{v}} \tag{13}$$

Let ξ and ω_n be the damping ratio and the undamped natural frequency of the yaw channel, respectively, then we have

$$2\xi\omega_\mathrm{n} = -(y_\mathrm{n} + n_\mathrm{r}), \quad \omega_\mathrm{n}^2 = y_\mathrm{n} n_\mathrm{r} + U_0 n_\mathrm{v} \tag{14}$$

It can be seen that the characteristics of the open-loop responses in Eqs. (12) and (14) are determined by the related aerodynamic derivatives. For example, to ensure that the open-loop yawing motion (i.e., without control) is stable, we must have $y_\mathrm{v} + n_\mathrm{r} < 0$. If the open-loop motion is unstable or is near the margin of instability, then autopilot must be installed to form a closed-loop system that integrates missile dynamics, sensor units, controller units, actuator units, and follow-up units as a complete missile control system as described at the beginning of this article.

Classic Control Design

Figure 4 depicts the block diagram of a lateral autopilot performing side force control, where a rate gyro measuring yaw rate and an accelerometer measuring side acceleration are used as feedback sensors. The missile's aerodynamic transfer function in Fig. 4 are obtained from Eq. (10). The controller is in the form of proportion and integration (PI). The problem of autopilot design is to design properly the seven parameters K_P, K_I, K_a, K_g, ξ_s, ω_s, and K_s such that the actual missile side force y follows the commanded side force y_d as quickly as possible. Among the seven parameters, the two controller gains K_P and K_I can be further tuned to satisfy different flight conditions. The remaining five parameters have fixed values and cannot be tuned on line. The selection of the seven parameters is aided by such tools as root locus, Bode, Nyquist, or Nicholls plots that enable visualization of how the system dynamics are being modified. The performance specifications of the side force response may be given in the frequency domain (e.g., bandwidth and gain/phase margins) or in the time domain (e.g., overshoot, damping ratio, rise time, and settling time).

The classic control design process of missile autopilot can be summarized in the following steps. Detailed procedures and practical design examples can be found in Refs. 5 and 11. How aerodynamic derivatives affect the missile autopilot design is discussed in Ref. 12. A useful review of classically designed autopilot controllers may be found in Ref. 13, where the relative merits of proportional and PI autopilot controllers are discussed and the novel cubic autopilot design is introduced.

1. Based on the system requirements analysis, the designer selects a flight control system time constant, a damping ratio, and an open loop cross-over frequency that will meet the system requirements for homing accuracy and stability.
2. The autopilot gains are calculated. The gains such as K_P and K_I in Fig. 4 are obtained in a variety of linearized flight conditions and must be scheduled by appropriate algorithms to account for the changing environment.
3. A model of the flight control system is developed. Initially the flexible body dynamics are neglected and the rigid body stability is analyzed to determine if adequate phase and gain margins have been achieved. If not, the response characteristics are modified and the design is iterated.
4. When the low-frequency design is complete, the flexible body dynamics are incorporated into the frequency models, and the stability is reexamined. For typical tactical homing missiles, the flexible body model should include the first, second, and third resonant mode dynamics of the pith and yaw channels and at least the first mode of the roll channel. Depending upon the characteristics of the roll airframe structure, additional modes may have to be modeled.

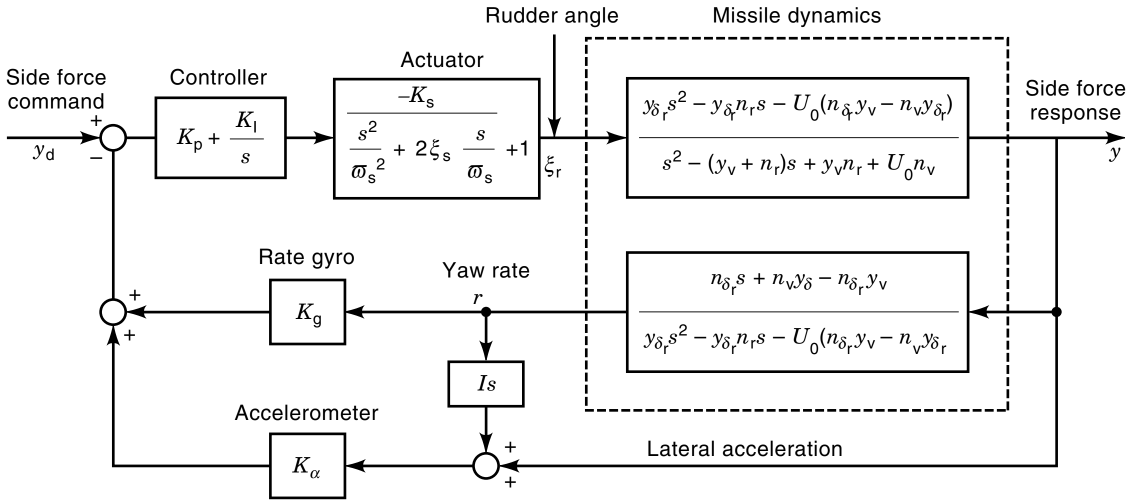

Figure 4. An autopilot structure performing side force command tracking. Both missile and rudder servos are modeled as second-order dynamics; the gyro and accelerometer are modeled as constant gains; and the controller is in the form of proportion and integration with tuning gains K_P and K_I.

5. In cases where the stability margins do not meet the design criteria the autopilot design is modified through adjustment of the autopilot gains and/or the inclusion of structural filters that adjust the gain or phase in the area of the natural resonances.

Modern Control Design

Classic control techniques have dominated missile autopilot design over the past decades. Autopilot design for future missile systems will be dominated by the requirement of ultimate agility in the entire flight envelope of the missile. Critical issues in the next generation autopilot will include (1) fast response to the commanded accelerations, (2) high maneuverability and guaranteed robustness over a wide range of mission profiles at all speeds and altitudes, (3) performance robustness against uncertainties in the aerodynamic derivatives, in the thrust profile, in the effectiveness of the control surfaces, and in the varying mass and moment of inertia, (4) cancellation or attenuation of highly nonlinear and coupled missile dynamics as a result of high AOA. The development of eigenstructure assignment, linear quadratic regulator (LQR) control, robust control, nonlinear control, adaptive control, and intelligent control techniques have revolutionized missile control system design considerably. They provide power tools to realize the aforementioned critical issues. Reference 14 provides an excellent discussion of various applications of modern control theory to flight control systems.

Eigenstructure-Assignment Autopilot Design. Eigenstructure assignment is the multivariable extension of the root locus method. The behavior of a MIMO system is characterized by eigenvalues and eigenvectors. The eigenvalues determine stability, and the eigenvectors characterize the shape and coupling of different modes. The technique is concerned with the placing of eigenvalues and their associated eigenvectors by feedback, to satisfy directly closed loop damping, settling time, and decoupling specifications. A review of eigenstructure assignment for aerospace applications can be found in Ref. 16. The technique has been applied to the control of the extended medium-range air-to-air missile in Ref. 17.

LQR Autopilot Design. LQR control theory is a well-established control system design technique (18). The LQR control gains are all obtained simultaneously from the minimization of a suitable performance index (usually the integral of a quadratic cost function). The design is synthesized in the time domain as opposed to the complex frequency domain. Reference 14 demonstrates the effectiveness of LQR design techniques for the missile flight control problem—describing the application of various LQR formulations to the design of single-plane lateral acceleration autopilot controllers. Reference 19 further considers the advantages obtainable by combining classical PI and modern LQR methodologies for a multivariable airframe model with high frequency structural modes.

Robust Autopilot Design. Robust control methods provide the means to design multivariable autopilots that satisfy performance specifications and simultaneously guarantee stability when the missile deviates from its nominal flight condition or is subject to exogenous disturbance. Several investigations have been undertaken specifically to research missile autopilot robustness. Early work was directed toward specific configurations and problems (20), with more recent work using the robust control system synthesis techniques of quantitative feedback theory (QFT) (21), H_∞ control (22), μ-synthesis (23), normalized coprime factor loop-shaping H_∞ control (24), and linear matrix inequality (LMI) self-scheduling control (25). Research has also been carried out on a number of related ways of assessing the robustness of missile autopilot controller design (26). A good literature survey in robust autopilot design can be found in Ref. 15. The robust control design is formulated to minimize the following effects:

- *Parameter Variation.* Aerodynamic derivatives, moment of inertia, and the center of gravity may have significant variations over the entire missile flight envelope.

- *Coupling Dynamics.* The residual error caused by inexact cancellation in decoupling pitch and roll–yaw dynamics for BTT missiles needs to be addressed.
- *Unmodeled Dynamics.* Most missile autopilot design consider missile rigid-body dynamics only, and the missile flexible modes are regarded as unmodeled dynamics. Robust control design allows the unmodeled dynamics to be taken into account to avoid structural vibration or instability.
- *Sensor Noises.* Autopilot needs to attenuate the effects caused by sensor noises, calibration errors, drifts, and parasitic dynamics.
- *Tracking Error.* A successful missile interception depends on the ability of autopilot to track the guidance commands. The uncertainties and noises in the seeker output and in the prediction of target maneuvers may affect the autopilot tracking performance.

Nonlinear Autopilot Design. Nonlinear control techniques used in missile autopilot design include feedback linearization (27), variable structure control (VSC) with a sliding mode (28), and nonlinear H_∞ control (29). The motivations of nonlinear autopilot design come from the concerns of the three common kinds of missile nonlinearities: dynamic couplings, nonlinear aerodynamics, and actuator limitations.

- *Dynamic Couplings.* Missile dynamics are coupled kinematically and inertially. The kinematic coupling terms can be isolated by casting the missile dynamic equations in the stability axes, whereas the inertial couplings, such as the roll–yaw coupling into pitch, can be accommodated by the feedback linearization approach because the extent of coupling is measurable.
- *Nonlinear Aerodynamic.* Nonlinear aerodynamics are the result of the nonlinear and uncertain characteristics of the stability coefficients and control coefficients. A nonlinear control scheduling, as a function of Mach number, AOA, dynamic pressure, and so on, can be designed to remove control uncertainties caused by nonlinear aerodynamics and to approximately equalize the control effectiveness.
- *Actuator Limitations.* The missile control surfaces have their limitations in the amounts of deflection and deflection rate. To avoid saturating the control surfaces, a command-limiting mechanism designed by dynamic inversion analysis needs to be implemented. Nonlinear dynamic inversion analysis also leads to an early understanding of design limitations, fundamental feedback paths, and a candidate feedback control structure. References 30 and 31 discuss some techniques used in nonlinear autopilot design.

Adaptive Autopilot Design. Adaptive control systems attempt to adjust on-line to accommodate unknown or changing system dynamics as well as unknown exogenous system disturbances. There are two general classes of adaptive control laws: direct and indirect. A relatively simple indirect adaptive control solution for the autopilot design challenge is gain scheduled adaptation (32), where the autopilot is designed offline for a number of operating conditions and the required gains are prestored against related flight conditions. In contrast, direct adaptive controls such as the self-tuning regulator (33) and model reference adaptive control (34) update the autopilot gains directly on the basis of the history of system inputs and tracking errors.

Intelligent Autopilot Design. Missile autopilot design task requires tuning parameters to achieve desirable performance. By augmenting a neural network in the tuning process, the parameter adjustment process can be standardized. This can be done as follows. First, build the desired flying qualities into the performance model. The autopilot structure is prefixed with the parameters undetermined. Then by comparing the actual system performance with the desired flying qualities, the neural network is trained to learn the rules of tuning. Accordingly, the autopilot parameters can be updated to meet the requirements. Application of neural network techniques to missile autopilot design and to future generation flight control system was investigated in Refs. 35 and 36.

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MISSILE CONTROL. See Missile guidance.