Solving an Age-Old Debate: What Really Controls Altitude and Airspeed?

Paper presented at A^{3}IRCON 2015

Juan Merkt
Department of Aeronautical Science
Embry-Riddle Aeronautical University, Prescott Campus
merktj@erau.edu

Abstract

Mismanagement of altitude and/or airspeed is linked to the top three causes of fatal aviation accidents: *loss of control inflight* (LOCI), *controlled flight into terrain* (CFIT), and *runway excursions* during approach and landing (RE). Clearly, the ability to control altitude and airspeed is a critical skill that all pilots must learn. Yet, differing opinions of how the throttle and elevator work to control altitude and speed can lead to confusion in the cockpit. Energy management is an effective approach to learn how the controls work and clear up the confusion. Unfortunately, energy principles have not found their way into primary flight training. To help bridge the gap, this paper discusses four basic principles of energy-based altitude and speed control.

Introduction

Poor management of the airplane's energy can be deadly. A significant number of fatal aircraft accidents—resulting from *loss of control in flight* (LOCI), *controlled flight into terrain* (CFIT), and *runway excursions* during approach and landing (RE)—has been associated with mismanagement of vertical flight path (potential energy) and/or airspeed (kinetic energy) (Airbus, 2005; Clark, 2005; Cox, 2010; Jacobson, 2010).

The airplane is a remarkable energy system—constantly transforming, transferring, distributing, storing, and exchanging various forms of energy as it moves through the air. Viewing the airplane as an energy system can enhance a pilot's understanding of the role of the flight controls for managing its energy safely. Unfortunately, energy principles associated with motion control, though well established in other disciplines, have not found their way into flight education. As a result, energy management skills, founded on those guiding principles, are not adequately taught or evaluated in primary flight training (Merkt, 2013; 2014).

This paper, adapted from an article that appeared in *SAFE the Magazine* (Merkt, 2014), bridges the training gap by focusing on four energy principles not sufficiently covered in flight training: *energy coupling between altitude and speed*, *energy balance*, *energy integration of flight controls*, and *energy error management*. For a more detailed account of flight energy management training see Merkt (2013).

Energy coupling between altitude and airspeed

Altitude and airspeed, the essential elements of flight, are inescapably linked through the laws of energy conservation and motion—they are *inseparable*. The combined energy stored as altitude and airspeed makes up the airplane's total mechanical energy. Put differently, the airplane's total mechanical energy is always distributed between altitude (potential energy) and airspeed (kinetic energy). In fact, the airplane's energy state is defined as the total amount *and* distribution of energy over altitude and airspeed (Merkt, 2014).

Altitude and airspeed are not only inseparable—they are also *interchangeable*. Thus, we can trade altitude for speed and vice versa without changing the airplane's total mechanical energy (at least in the short term). Given the energy coupling between altitude and speed, any attempt to change one independently of the other by using a *single* control (e.g. throttle or elevator) always fails (Merkt, 2014).

The airplane's energy balance

A flying airplane is an *open energy system*. In other words, energy can be *added* to or *removed* from the total mechanical energy *stored* in the airplane. An airplane stores mechanical energy in the form of altitude and speed. Once flying, the airplane gains energy from engine *thrust* (*T*), the propulsive force generated from burning fuel, and loses energy through aerodynamic *drag* (*D*), the retarding force that releases heat into the surrounding air (Amelink et al., 2005; Rutowski, 1954). As a result, energy flows continuously into and out of the flying airplane. More importantly, there is a direct relationship between the net energy flowing *through* the airplane and changes in the total energy stored *in* the airplane (Rutowski, 1954). This fundamental relationship, derived from the law of energy conservation, is the airplane's energy balance[1]:

$$\text{Energy gained from thrust } (T) \; - \; \text{Energy lost through drag } (D) \; = \; \text{Change in potential energy (altitude)} \; + \; \text{Change in kinetic energy (airspeed)}$$

The left side of the equation—a function of the *difference* between thrust and drag ($T - D$)—controls the net *transfer* of energy into or out of the airplane; while the right side controls the *distribution* of the resulting change in total energy between altitude and airspeed. More importantly, any difference between energy gain and loss (on the left side) is *automatically* matched by an equal change in the airplane's total energy (on the right side). Thus, even though

[1] The airplane's energy balance is usually expressed as a rate equation in units of energy/time (power). Note that the simplified equation depicted here does not account for the change in total mechanical energy caused by the change in aircraft weight as fuel is gradually burned in flight. Although the effect of weight change is negligible when applying the energy approach to solve short-term control problems (as we are doing here), it becomes critical when solving long-term performance problems such as those involving range calculations.

the left and right sides may change in value, an energy balance is *always* maintained in steady or non-steady flight. In a perfect balancing act, as the left-hand moves energy into or out of the airplane by the action of two forces (*T* and *D*), the right-hand takes the resulting change in total energy and redistributes it over altitude and/or airspeed (Merkt, 2014).

Thus, when energy gained exceeds that spent ($T – D > 0$) a net flow of energy into the airplane increases its total energy. The airplane redistributes and saves that surplus energy, not needed to "pay" for drag, into additional altitude or speed. When energy gained is less than energy spent ($T – D < 0$) a net flow of energy out of the airplane decreases its total energy. Here the airplane redistributes the net energy loss by descending or slowing down as energy is transferred out to help pay for drag. Finally, when energy gained matches energy spent ($T – D = 0$) there is no net gain or loss—all thrust is spent on drag—as the airplane maintains constant altitude and airspeed (Merkt, 2014).

What then controls "$T – D$" on the left side of the equation, and what controls the distribution of energy between altitude and airspeed on the right side? To answer these questions, we turn to the role of the throttle and the elevator.

Energy-based integration of the flight controls

The airplane has two primary devices to control altitude and airspeed: the throttle and the elevator. The question is: which device controls altitude and which one controls airspeed? In one of the oldest debates in aviation, some pilots believe that the throttle controls airspeed and the elevator controls altitude, while others subscribe to the opposite view. Which side is right? As it turns out, neither is right. Because of the inherent energy coupling between altitude and airspeed, any attempt to change one variable (e.g. altitude) with a single control (e.g. elevator) always results in a change in the other variable (e.g. airspeed). Thus, neither the throttle nor elevator controls altitude and airspeed independently (Amelink et al., 2005; Lambregts, 1983; Merkt, 2014).

The solution? To effectively change altitude and airspeed, the throttle and the elevator must be coordinated following energy management principles. Both devices are really energy controls. The throttle, by increasing or decreasing thrust, regulates the *rate of change of total mechanical energy* (Amelink et al., 2005; Lambregts, 1983; Merkt, 2014). The latter is a function of both thrust (energy gain) and drag (energy loss), however drag varies mainly due to long-term changes in airspeed or deployment of high lift/drag devices that can only increase drag. Therefore, changes in total energy—demanded by new or corrective maneuvers—are normally initiated by changing thrust, not drag. Long-term, thrust can be re-trimmed to compensate for changes in drag (Lambregts, 1983; Merkt, 2014).

What about the elevator? This control, used for trading altitude for airspeed and vice versa, is an energy exchanger. Thus the elevator, which per se does not contribute to energy gain or loss, is an *energy distribution* device whose primary job is to correctly allocate changes in total energy between altitude and speed (Amelink et al., 2005; Lambregts, 1983; Merkt, 2014).

A reservoir analogy (Figure 1), adapted from Amelink et al. (2005), illustrates the integrated role of the throttle and the elevator in managing the airplane's energy. As shown in the diagram, the airplane gains energy through thrust (T) and loses energy through drag (D). The net transfer of energy, resulting from the difference between thrust and drag, determines whether the airplane's total energy—the sum of the energy contained in the altitude and airspeed "reservoirs"—increases, decreases, or remains constant. The throttle regulates the net flow of energy into or out of the airplane, while the elevator controls the distribution of this energy flow between altitude and airspeed. In other words, *the throttle and elevator control the airplane's energy balance* —with the throttle controlling the "energy transfer" side and the elevator controlling the "energy distribution" side of the equation (Merkt, 2014).

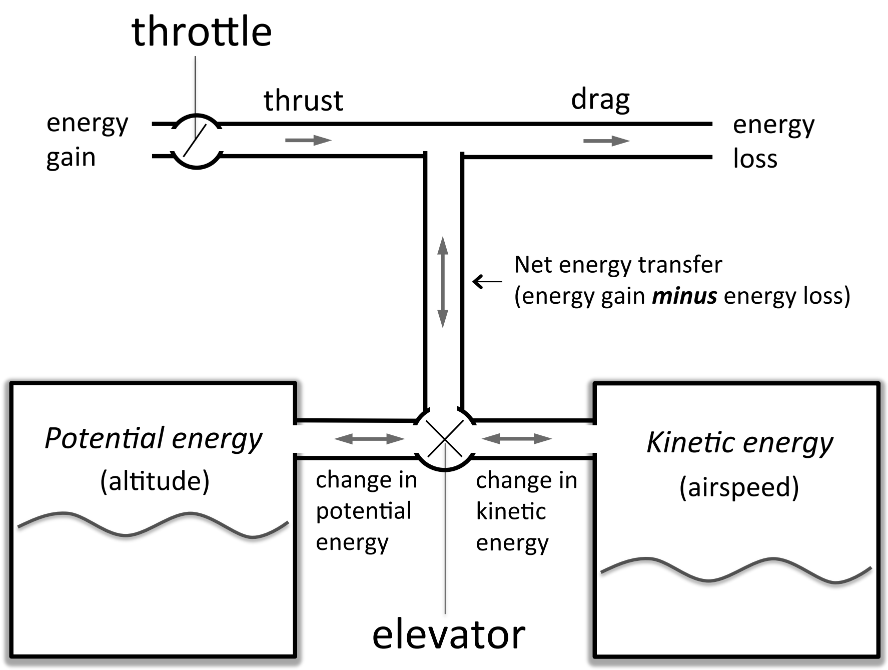

Figure 1. The reservoir analogy (adapted from Amelink et al., 2005) depicts the role of the throttle and elevator in controlling the aircraft's energy balance (see equation in previous section). The throttle controls the "valve" regulating the net total energy transfer while the elevator controls the "valve" regulating the distribution of energy between altitude and airspeed. The solid arrows represent energy flows, not relative direction of forces or airflows. Note that the net energy transfer (resulting from the difference between thrust and drag) can switch directions as energy moves into or out the "reservoirs".

When the throttle increases thrust above drag ($T – D > 0$), more energy flows into the airplane raising its total energy, and when the throttle reduces thrust below drag ($T – D < 0$), more energy flows out decreasing its total energy. The elevator then distributes this increase or decrease in total energy into or out of the altitude and speed reservoirs. Finally, when the throttle adjusts thrust equal to drag ($T – D = 0$), there is no net energy transfer, but the energy stored as altitude and speed can be exchanged using the elevator while total energy, in the short-term, stays constant (Merkt, 2014). Now that we understand the energy role of the controls, let's focus on how we can use them to minimize energy errors during flight.

Energy error management

Energy management is about making desired *changes* in vertical flight path and airspeed—when initiating a new maneuver (e.g. leveling off from a climb) or correcting deviations from the desired path/speed. Here I focus on the latter since most in-flight "energy crises" start as undetected or ignored deviations from the target flight path or airspeed. For example, being below the glide slope at a slower speed than desired on final is an unsafe deviation requiring prompt flight path and speed correction. Thus, an important aspect of learning to manage the airplane's energy safely and efficiently is to develop mitigation skills to recognize, correct and prevent energy errors (Merkt, 2014).

Since the airplane's total energy is distributed over altitude and airspeed, one can distinguish two types of energy state errors: 1) *total energy errors* and 2) *energy distribution errors* (Amelink et al., 2005). You can recognize these energy errors by monitoring the altimeter (or other flight path reference) and airspeed indicator.

Figure 2 depicts energy errors and corresponding altitude and airspeed deviations. In total energy errors, the airplane has too much or too little energy. As you scan the instruments, you will notice that altitude and speed deviate in the *same* direction (e.g. low-and-slow or high-and-fast). On the other hand, in energy distribution errors the airplane has the right amount of total energy but its distribution over altitude and speed is incorrect. Here, altitude and speed deviate in *opposite* directions (e.g. high-and-slow or low-and-fast). Just remember, we are dealing with relative deviations—*not* absolute altitude and speed (Amelink et al., 2005; Merkt, 2014).

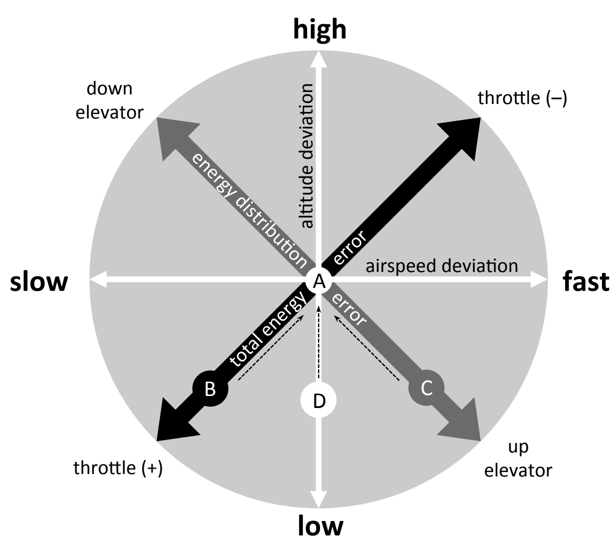

Figure 2. In total energy errors altitude and airspeed deviate in the same direction, while in energy distribution errors altitude and airspeed deviate in opposite directions. Total energy errors are corrected by increasing or decreasing energy with the throttle. On the other hand, energy distribution errors are corrected by exchanging energy

with the elevator. Correcting a combination of total energy and distribution errors requires the use of both throttle and elevator. Note that the scaling in the figure has been simplified to show an apparent one-to-one matching between altitude and speed deviations.

Following energy management principles then, you correct total energy errors by increasing or decreasing energy using the throttle, and energy distribution errors by exchanging energy between altitude and speed using the elevator. For example, when flying an ILS approach, being low and slow ("B" in Figure 2) is fundamentally different from being low and fast ("C" in Figure 2). The airplane is lower than desired in *both* cases, but the former deviation calls for adding thrust with the throttle to increase total energy while the latter one calls for up elevator to null the energy distribution error (Figure 2). Finally, to correct a combination of total energy and distribution errors requires using *both* controls. Being lower than desired but at the correct airspeed on final ("D" in Figure 2) is an example of a combination of total energy and distribution errors. In this case, regaining altitude without changing speed, calls for adding power while pulling back on the yoke (Figure 2). In other words, decoupling altitude and speed (i.e. changing one without changing the other) requires simultaneous use of both controls (Amelink et al., 2005; Merkt, 2014).

In all cases, once energy deviations are corrected ("A" in Figure 2), the airplane will need to be trimmed to maintain the desired vertical flight path and airspeed (Amelink et al., 2005; Merkt, 2014).

Conclusion

Managing the airplane's energy is essentially a "balancing act"; best embodied by the energy balance equation. On the surface, the energy balance equation is a simple equality that applies to any phase of flight—where a change in the amount of energy flowing *through* the airplane is matched by an identical change in the total energy stored *in* the airplane. But as we examine the equation more carefully, we discover other "balancing acts" (Merkt, 2014).

On the left side of the equation, a "tug-of-war" between two opposing forces—thrust and drag—determines whether the airplane's total energy will increase, decrease, or remain constant. On the right side, any resulting change in the airplane's total energy is redistributed over altitude and/or airspeed. If energy were cash, the left side would account for changes in the airplane's "cash flow," while the right side would reflect matching changes to the balance in the airplane's altitude and speed "savings accounts." (Merkt, 2014).

The master performers in the airplane's energy "balancing act" are the throttle and the elevator. Any desired changes in energy on both sides of the balance equation (e.g. to initiate a new maneuver, or to correct trajectory/speed deviations) call for a balanced coordination of the throttle acting on the left side and the elevator acting on the right side. By regulating engine thrust, the throttle controls the net transfer of energy and thus the rate of change of the airplane's total energy, albeit imperfectly since the throttle cannot regulate aerodynamic drag. The elevator, which *per se* does not contribute to energy gain or loss, is simply an energy distribution device whose primary role is to correctly allocate changes in total energy between altitude and speed (Merkt, 2014).

Ultimately, a pilot is an energy manager. Understanding energy management can help master the coordination of the controls for controlling altitude/flight path and airspeed safely. Following the four principles outlined in this paper will give pilots a head start.

References

Airbus. (2005). Aircraft energy management during approach. Airbus Customer Services, Flight Operations Briefing Notes. Retrieved from http://www.airbus.com/fileadmin/media_gallery/files/safety_library_items/AirbusSafetyLib_-FLT_OPS-APPR-SEQ03.pdf

Amelink, M. H. J., Mulder, M., van Paassen, M. M., & Flach, J. M. (2005). Theoretical foundations for a total energy-based perspective flight path display. *The International Journal of Aviation Psychology, 15 (3)*, 205–231.

Clark, D. (2005). Approach and landing accident reduction (ALAR) and energy management. The Mobility Forum. May/June 2005, 4-6.

Cox, J. M. (2010). Prioritizing mitigations in flight path management accidents. Safety Operations Systems: Technical Rep. June 2010. Retrieved from http://www.safeopsys.com/docs/Flight_Path_Accidents.pdf

Jacobson, S. R. (2010). Aircraft loss of control: Causal factors and mitigation challenges. American Institute of Aeronautics and Astronautics, 2010-8007. AIAA Guidance, Navigation, and Control Conference, Toronto, Ontario, Aug. 2-5, 2010.

Lambregts, A. A. (1983). Integrated system design for flight and propulsion control using total energy principles. In *AIAA Aircraft Design, Systems and Technology Meeting*. AIAA-83 2561.

Merkt, J. R. (2013). Flight energy management training: promoting safety and efficiency. *Journal of Aviation Technology and Engineering, 3(1)*, 24–36.

Merkt, J. R. (2014). Balancing act: managing aircraft energy. *SAFE the Magazine*, Summer 2014. An online publication of the Society of Aviation and Flight Educators. Retrieved from http://safemagazine.org/article/balancing-act-managing-aircraft-energy

Rutowski, E. S. (1954). Energy approach to the general aircraft performance problem. *Journal of the Aeronautical Sciences 21*(3), 187-195.