HOW A CRUISE MISSILE WORKS

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The tomahawk cruise missile can fly a 1000 miles and hit a target the size of a car and is a crucial element of the American weapons arsenal. This paper explains how a cruise missile works. It will focus on the cruise missile's launch, flight, low radar visibility and its guiding systems.

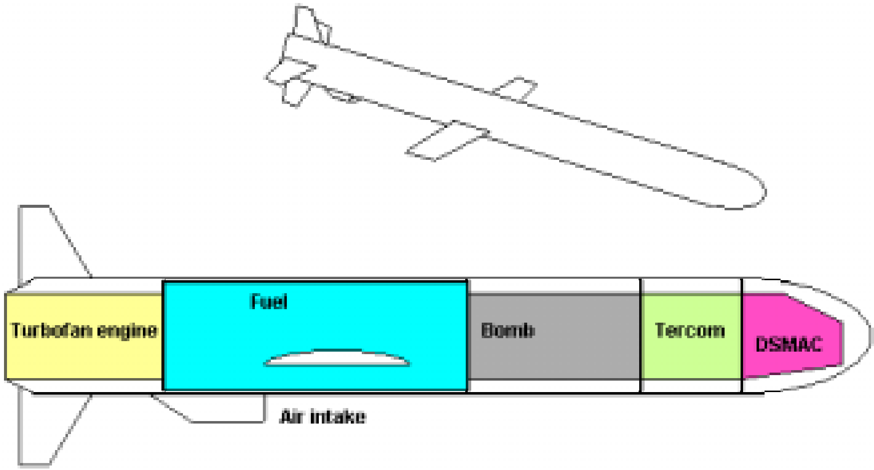

Figure 1

In essence, the cruise missile is a small plane without a pilot. It is 6.25 m long and 0.52 m in diameter. As figure 1 shows, the missile incorporates a turbofan engine, a fuel tank, a conventional bomb, air intake and four different guiding systems. At launch a loaded cruise missile weighs about 1450 kg. A solid rocket booster causes the initial acceleration and launch of the cruise missile. After that the turbofan engine takes over, propelling the missile to a cruising speed of 880 km/h.

The acceleration of a cruise missile and its flight involve Newton's second and third laws of motion. Newton's third law says that "to every action there is an equal and opposite reaction". This law can explain how the solid rocket booster causes the missile's initial acceleration. The propellant in the rocket booster burns very fast and this reaction produces mostly gasses (mainly CO_2). The core of the propellant is hollow and it burns out from the middle so that the gas accelerates through the hollow core out of the back of the solid rocket booster.

The rate at which the burnt propellant gasses come out of the solid rocket booster depends on the difference in pressure between the core of the rocket booster and the pressure outside. The pressure inside the rocket booster is very high as the gas density is high and the gas is hot. In order to increase the booster's efficiency, the nozzle is small. As the gas rushes out of the booster through the small diameter nozzle, the gas accelerates very quickly (this is called the Venturi effect). As the gas accelerates, it converts potential energy into kinetic energy.

The force necessary to accelerate the gas equals the mass of the gas times the magnitude of its acceleration (Newton's second law of motion ($F=m\cdot a$). Although the mass of the gas may not be a lot, therefore, the huge acceleration of the gas causes the force necessary for the acceleration to be substantial. Newton's third law of motion says that a force equal but opposite the force necessary to accelerate the mass of the gas is pushing on the cruise missile and accelerating it. This force accelerates the missile according to $F=m\cdot a$. If the solid rocket booster was completely efficient, therefore, the ratio of the acceleration of the gas and the cruise missile equals the ratio of the weight of the propellant and the missile.

When the solid rocket booster burns out, it falls away and a turbofan engine takes over. At this time, the cruise missile's wings also fold out in order to keep the missile airborne. This process also rests on Newton's laws of motion. In essence, the lift of the wings is base on the same principle as the thrust of the solid rocket booster; they both hurl down gas, so that the reaction force pushes the missile upward. The difference is that the missile's wings use the air around them, while the booster uses the gaseous reaction products of the burning propellant. When the cruise missile's wings "cut" through the air, they redirect air downward. This is acceleration so that the wing must apply force to the air to redirect it. This means that there is an equally large force pushing upward on the wing. This force keeps the missile airborne.

Once in flight the cruise missile has the major advantage that it can fly very low to the ground and evade radar. The physics of radar can explain how this works. Radar uses the reflection of microwaves of objects to determine their location. As all electromagnetic waves, microwaves are composed of an electric and a magnetic field that recreate each other as the wave moves through space. In order to create microwaves, a magnetron sloshes electric charges up and down an antenna (ideally about one fourth of the wavelength). Depending on the frequency of the sloshing, microwaves have wavelengths between 1 mm and 1 m.

When the radar sends out pulses of microwaves, they reflect off metal surfaces back to a detector. When hitting the metal, the microwave pushes on the charges in the metal and accelerates them. These accelerating charges prevent the wave from entering the surface and reflect it instead. A detector picks up the reflected pulses of the microwave and keeps track of time. The time difference between when the signal was sent out and the when the detector picks it up allows the radar-device to calculate how far away the object is located. The distance between the radar and the object equals speed of light ($2.99\cdot 10^8$ m/s) times the time difference divided by 2 (the microwaves have to go back and forth).

The cruise missile evades this kind of detection by flying very low, so that it is invisible to radar. This invisibility has to do with the curvature of the earth, the surface of the earth and the fact that microwaves travel through space in straight lines. If the missile stays close to the ground, the microwaves of the radar cannot reach it, as the wave bounces of mountains and other obstacles. When the cruise missile is even further away (about 100 km), the curvature of the earth can protect it, as the straight microwaves cannot follow the shape of the globe.

During its flight, four different guiding systems guide the cruise missile to its target. Two of these guiding systems will be discussed here. Firstly, during its flight, the cruise missile "knows" how far and where it has traveled through its IGS (Inertial Guidance System). The IGS is based on Newton's first law of motion, namely that an object that is not subject to any outside forces moves at a constant velocity (i.e. that masses have inertia, hence the name). The IGS involves three mutually perpendicular gyroscopes and three mutually perpendicular accelerometers.

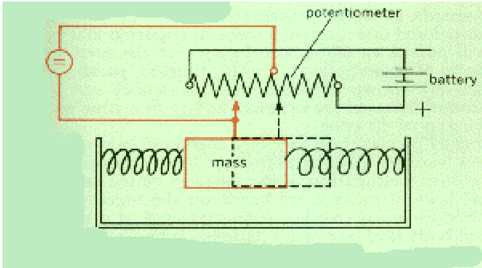

Figure 2

Consider figure 2 depicting the electrical circuit of an accelerometer. The mass is contained between two springs, and connects to a potentiometer (essentially a variable resistor). When the cruise missile is at rest or travels at constant speed, the mass stays at rest and the potentiometer at 0. When the missile accelerates in a particular direction, the mass lags behind, due to its inertia. The potentiometer is set up so that it gives a positive voltage when the missile accelerates and a negative voltage when it decelerates. Based on these voltages, a computer can derive the magnitude and direction of the cruise missile's acceleration and consequently its speed. With this speed and the time, the IGS can calculate how far the cruise missile has flown and in what direction, and consequently its position relative to some reference point.

Due to imperfections in the gyroscopes, however, the inaccuracies of the IGS accumulate over time. The IGS on the cruise missile can be off by up to 900 m per hour! To complement the IGS, the cruise missile is fitted with the Global Positioning System (GPS). This system is based on 24 satellites orbiting the earth. These satellites are positioned so that the receiver on board the cruise missile is able to pick up electromagnetic waves (at both 1575 MHz and 1228 MHz) from more than 4 satellites. From the digital satellite signal, the receiver knows when the satellites sent out the signal. By measuring how long it takes for the electromagnetic waves from the satellites to reach the receiver, it can calculate its distance from that satellite. It uses these distances to accurately determine its position, by a geometrical process called triangulation. The essence of this method is the fact that three spheres intersect at two points at the most. One of these points is usually a ridiculous reading so that that one can be discarded without further measurement. The combination of the distances from the three satellites basically allows the GPS to determine its position relative to the system of satellites. Together with an almanac of where each satellite is at what times, this knowledge allows the GDP receiver to know where its is on earth.

One essential condition for GPS to work is that the clocks in the satellites and the time the receiver uses are very accurate and perfectly in sync. The satellites use very accurate atomic clocks to measure time. The Ce-atomic clocks on board the GPS satellites are based on stimulated emission. Cesium-133 atoms emit a thin microwave spectral line when its 55th electron jumps back from an excited state orbital to its ground state (transition). The atomic clocks on board the GPS satellites use this frequency, $9.192631770 \cdot 10^9$ Hz, to very accurately keep time. As atomic clocks are very big, however, there is no atomic clock in the GPS receiver on board the cruise missile. However, with a fourth reading, the GPS receiver can be largely synced with the atomic clocks on the satellites.

Besides the problem of syncing the clocks, the GPS system has to overcome the fact that the electro-magnetic waves do not always travel at the speed of light. The atmosphere slows down the electro-magnetic wave. However, low frequencies get slowed down more than high frequency signals. The GPS receiver on board the cruise missile detects both signals and measures the difference in how long its took them to reach the receiver. Then the receiver uses this fact to determine how much the atmosphere has slowed down the signals and corrects for.

With the help of GPS, IGS, solid rocket boosters, flight, and radar invisibility the cruise missile delivers its 1000 pounds bomb to its target. Once that job is well done, the explosion of its bomb destroys the million dollar missile. It’s ironic that in monetary terms the greatest damage the cruise missile does may often be destroying itself.

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