Dynamic Modeling of Two-Part Missiles

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ABSTRACT

A missile can be defined as any object that can be thrown, projected or propelled toward a target [1]. In other words, a missile is a projectile carrying a payload (usually a warhead) which is guided onto a target by manual or automatic means [4]. Obviously, it is primarily used as a weapon in order to give damage to the target.

Missiles can be classified into different categories. Depending on how they are oriented toward the target, they can be categorized as unguided and guided missiles [1]. Unguided missiles, whether initially or continuously propelled, can be oriented toward their targets only before they are fired. After firing, they get completely out of control. Therefore, they can be used with acceptable effectiveness only for short distance and stationary targets; because, for moving targets or for targets at longer distances, the hitting accuracy drops more and more due to various reasons such as aiming errors, crosswinds, curvature and rotation of the Earth, etc. The unguided missiles are especially ineffective against moving targets unless such targets are particularly close and slowly moving. Guided missiles, on the other hand, can be used effectively both for distant and arbitrarily moving targets because the motion of a guided missile keeps being observed or reckoned and any deviation from a commanded motion is corrected during its flight [1], [2], [3].

The guided missiles can be categorized into two groups depending on the operational range [5]: tactical missiles and strategic missiles. While tactical missiles are used in short and medium range scenarios and they are in general guided to the target by some kind of sensors such as seekers, strategic missiles are different from the tactical ones because they travel much longer distances and are designed to intercept stationary targets whose location is known precisely [5].

Regarding the guided missiles, the guidance and control problem involves four sequential stages: dynamic modeling, guidance, control, and motion estimation of the target. In the dynamic modeling stage, the missile is modeled so as to get the relationships among the selected input and the output variables. Then, the guidance algorithm is developed in order to guide the missile toward the intended target for an expected interception. Once the guidance algorithm is constructed, the next step is to design a control system based on the

dynamic model of the missile so that it obeys the command signals generated by the guidance unit. The last stage is the estimation of the kinematic parameters of the target. For this task, it is conventional to use a state estimator algorithm such as Kalman filter or fading memory filter.

As mentioned above, it is a primary requirement to obtain the relationships among the forces/moments acting on the missile and the kinematic state, i.e., position and velocity, of the missile in order to design a control algorithm. The external forces and moments acting on a missile are those generated by the aerodynamic effects including control surfaces, the propulsion including control thrusters, and the gravity [6], [7]. As the results of these effects, the components of the position vector of the missile along the downrange, crossrange and altitude directions change as well as the yaw, pitch and roll attitudes.

It turns out that it is easier to model the inertial forces and moments than the aerodynamic force and moment components. The aerodynamic force and moment terms are dependent both on the present and past values of the kinematic parameters of the missile. In order to model the aerodynamics of the symmetric missiles, one of the widely used methods is the Maple-Synge analysis [8]. With this method, the aerodynamic force and moment coefficients are related to the kinematic flight parameters by means of certain functions. For the sake of designing an autopilot, or the controller of missile control system, these coefficients are in general expressed as linear functions of angle of attack, side-slip angle, or skid angle, effective fin deflections, and body angular velocity components [9], [10], [11], [12], [13]. Also, some analytical methods have been developed in order to predict the nonlinear aerodynamic forces and moments acting on a missile undergoing steady and unsteady maneuvers [14]. Some researchers have turned to neural networks as a means of explicitly accounting for uncertain aerodynamic effects [15]. In modeling the aerodynamic forces and moments, the effect of aerodynamic drag on the missile is usually ignored because it causes only a slow change in the speed. As a result of this, the missile speed is treated to be almost constant throughout the after-boost phase [16].

In the sense of the existence of the thrust effect, the motion of the missile can be primarily divided into two successive phases: boost phase and after-boost phase. As its name implies, the boost phase comprises the flight of the missile from the firing instant to the end of the thrust. Because the thrust supplied by the solid propellant in the rocket motor causes the missile to move ahead, the dynamics of the missiles in the boost phase can be modeled considering the nonzero effect of the thrust force and thus the changing mass [1], [10]. In the after-boost phase, the inertial parameters of the missiles, i.e., its mass and moment of inertia components, remain unchanged.

Although almost all of the guided missiles are single-body structures, there are also rarely seen two-body structures. An example is the so-called “Advanced Precision Kill

Weapon System (APKWS)". In this structure, the guidance section is mounted onto the motor section using a deroll bearing which permits the motor to roll freely while the guidance section is roll stabilized. The roll bearing causes unusual dynamic properties for this missile design because the airframe has two separate sections rolling at different rates. This fact creates additional dynamic coupling between the pitch and yaw channels of the missile [17]. Like APKWS, the missile model dealt with in this study is also a two-body structure whose parts are connected to each other by means of a roller bearing [18].

In this study, the dynamic modeling of a missile with two relatively rotating parts which are connected to each other by means of a roller bearing is dealt with. Completing the full kinematic analysis of the considered missile model, its governing differential equations of motion are derived along with the aerodynamic force and moment terms. Finally, the necessary transfer functions to be used in the control system design stage are determined based on the derived equations of motion.

Keywords: Two-part missile, homing missile, dynamic modeling, aerodynamic modeling, and transfer function

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