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Robust roll autopilot design to reduce couplings of a tactical missile

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ABSTRACT

The purpose of this work is to decrease coupling effects of a tactical missile by designing a robust autopilot for its roll channel. In tactical STT missiles due to control strategy, in order to execute acceleration commands, roll angular velocity should be kept close to zero. Generally, in the design of autopilot for many of tactical missiles the inter influences of channels is neglected. However, three channels of the missile impact each other in different ways including kinematic, inertia and aerodynamic couplings. Aerodynamic coupling is a dominant in roll channel dynamics appearing as induced and control cross coupling roll moments. In this paper first the coupling terms are modeled considering literature. Next, the system is linearized as input–output using models of induced and control cross coupling roll moments. Also, for increasing robustness of the autopilot against modeling errors, uncertainties, and external disturbances, an uncertainty and disturbance estimation (UDE) controller is used. To evaluate the performance of the designed controller, the results were compared with three controlling methods namely a PD controller based on simple dynamics model, a PD controller based on modified dynamics model and a robust controller based on the extended state observer (ESO). Flight simulation results revealed that if the approximate relationship of induced and control cross coupling roll moments are appropriately modeled, UDE control performance outperforms other methods and couplings between pitch and yaw channels are significantly decreased.

1. Introduction

In this paper, a design of the roll channel autopilot of a tactical STT missile is developed. Missile guidance system is a homing type and control is performed by aerodynamic tail fins. The guidance system of an STT missile produces the required commands to direct it towards the target and these commands are supplied to the control system.

There are different strategies for performing these commands which are related to how the roll channel command is imposed. Considering this, missiles are classified as STT, BTT and RA. In STT missiles, which are the focus of this paper, both pitch and yaw channels are controlled and angular velocity of the roll is kept near zero to make applying acceleration commands faster. Therefore, the tracking quality of the guidance commands is dependent on the design of the roll channel autopilot.

Furthermore, different reasons like low moment of inertia of the missile around the longitudinal axis, uncertainty in aerodynamic coefficients, neglected dynamics, couplings, and external disturbances introduce great challenges in the design of roll channel autopilot.

In designing of an autopilot before the selection of a suitable controlling method, it is necessary to identify the effective factors of the system dynamics and proposed mathematical models. General design of an autopilot for many missiles is performed assuming the independence of roll, pitch and yaw channels.

Precisely speaking, this is a simplifying assumption and in practice these three channels have interactions known as coupling. The dynamics model of the missile's three channels relies on kinematic, inertia and aerodynamic couplings. The missile's dynamics translational equations include terms of linear and angular velocity multiplications introducing kinematic coupling. Moreover, terms of angular velocity multiplications define inertia coupling. Translational and angular dynamics equations of the missile show that the interaction of the pitch and yaw channels can be neglected only when angular velocity of the roll is adequately low [1].

Thus, the stabilization and desirable control of the roll rate leads to the elimination of the coupling terms and therefore better performance of the pitch and yaw channels. Of course, except in special cases, the roll channel dynamics is modeled without considering inertia couplings by assuming axial symmetry of the missile.

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Nomenclature

Abbreviation

BTT	Bank-To-Turn
CFD	Computational Fluid Dynamics
DGO	Das & Ghosal Observer
ESO	Extended State Observer
INA	Inverse Nyquist Array
IOL	Input–Output Linearization
LQR	Linear Quadratic Regulation
PD	Proportional-Differential
RA	Rolling Airframe
SISO	Single Input–Single Output
STA	Super Twisting Algorithm
STT	Skid-To-Turn
UDE	Uncertainty and Disturbance Estimation

Symbols

$(\vec{a}_T)_{Body}$	Target acceleration vector in target body coordinate
C_l	Non-dimensional roll moment coefficient
C_{l_I}	Induced roll moment coefficient
C_{l_p}, $C_{l_{\delta a}}$	Roll damping and controlling coefficients
I_{xx}, $I_{yy} = I_{zz}$	Longitudinal and lateral moments of inertia
K_{CC}	Multiplier parameter in equation of Control cross coupling roll moment
K_p, K_d	Proportional and differential gains of PD controller
L_{CC}	Control cross coupling roll moment coefficient
L_I	Induced roll moment coefficient
L_f	Lie derivative of f
L_p	Damping roll moment coefficient
$L_{\delta a}$	Controlling roll moment coefficient
$M_{x_{CC}}$	Control cross coupling roll moment
M_x	Roll moment
a_y, a_z	Lateral accelerations
d_{ext}	External disturbance
$\bar{q}$	Dynamic pressure
u_d	Control input for composite disturbance compensation
u_n	Control input for elimination of nonlinear terms
$y^{(r)}$	rth derivative of y
α_T	Total angle of attack
δ_e, δ_r	Elevator and rudder deflection
ϕ_A	Aerodynamic roll angle
D	Missile diameter
M	Mach No.
S	Missile cross-section area
V	Missile velocity
d	Composite disturbance
p, q, r	Roll, pitch, yaw angular velocities
v	New control input in feedback linearization
α, β	Angles of attack and side slip
τ	Time constant of low pass filter
φ	Integral of p
$\hat{}$	Represents the approximated value of a parameter

The most common way to model the roll channel dynamics is the simple one. In this model, the roll moment is produced merely by controlling and damping aerodynamic linear terms and other parameters like aerodynamic couplings are neglected. The optimized control method LQR is a commonly used way which is combined with classic control criteria [2]. An ESO observer is used to approximate composite disturbance and to improve the robustness of the controller [3]. The adaptive control method is used in order that the controller be independent of the number of structure twist modes [4]. The gains of proportional-differential classic control are computed using the pole placement technique [5]. State feedback technique and DGO observer are used to approximate states of the system [6]. The sliding control method based on the searching Lyapunov matrix is used to increase the robustness of the roll channel controller [7]. Furthermore, the sliding mode STA algorithm is used for the same goal [8].

Beside simple dynamics models, some sources have also considered aerodynamic couplings. These kinds of couplings are present due to the asymmetrical pressure distribution on the missile airframe. Results of wind tunnel experiments of the cruciform missiles show that in addition to the damping and controlling terms for the roll channel, there is an aerodynamic term called induced roll moment. The dominant reason for producing this moment is the asymmetrical direction of wind relative to the missile's body [9]. Moreover, in missiles controlled by aerodynamic surfaces, while applying control deflections a specific aerodynamic coupling called the control cross coupling is produced due to conflicts between tail fins and vortices separated from the body. This coupling can manifest in two different ways. The first way is the pitch and yaw moment due to aileron deflection and the second way is the roll moment from the elevator and rudder [10].

Besides the control cross coupling roll moment which is modeled linearly with respect to elevator and rudder deflections, modeling of the induced roll moment can be nonlinear or linear relative to airflow angles. Some of the references consider the linear couple model of the roll and yaw channels and neglect the pitch channel due to its similarity to the yaw channel.

Autopilot design is performed by decoupling system dynamics using the optimized INA method [11]. Furthermore, to decouple the roll and yaw channels in high angle of attack and low angle of side slip the multiplication of the trim lateral acceleration in rudder and aileron deflections is used [12]. In linear modeling of the induced roll moment some references have considered the effect of both pitch and yaw channels on the roll channel and integrated the design of all three channel autopilots. Feedback linearization, based on model reference adaptive control has been applied [13]. Moreover, robust control methods such as μ-synthesis [14] and H_2 [15] have been used for this model.

In most of the references the modeling of the induced roll moment is a nonlinear function of the Mach number and total angle of attack and a periodic function of the aerodynamic roll angle. Optimized classic control methods are applied to integrate the design of the three channels' autopilots. Also, prediction of the aerodynamic roll angle is applied to compute the induced roll moment and its compensation in the roll channel controller [16]. [10] models the effects of induced and control cross coupling roll moments for simulation. But only the control cross coupling roll moment is compensated using feedback linearization in the autopilot design process.

Reviewing the present literature for roll channel modeling shows that all effects of aerodynamic couplings are included in the integrated design of three channel missile autopilots. Besides, simultaneous compensation of the induced and the control cross coupling roll moments has never been focused. It should be noted that selecting an appropriate controlling method requires an exact mathematical model of the system which is not always available in practice. On the contrary, although classic control methods neglect the modeling of high order dynamics, they are very appropriate for practical application.