Status and Concerns for Bank-to-Turn Control of Tactical Missiles

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This paper provides a summary of the current status of autopilot development for antiair preferred orientation control tactical missiles and identifies the associated critical coupling paths and parameters impacting stability and control characteristics. In general, classical skid-to-turn autopilot architectures have limited applicability for preferred orientation control configurations due to the increased severity of dynamic cross-channel coupling paths. Attention to airframe design may alleviate the problem somewhat, but modified autopilot architectures still may be required to optimize performance. Technology issues related to development of autopilots and airframes with desirable characteristics are identified.

Preface

SEVERAL advanced antiair tactical missile programs sponsored by the Navy and Air Force are seriously considering designs which either must or could use preferred orientation control concepts throughout flight. Currently, there are no high-performance antiair missiles within the U.S. arsenal utilizing this technology. Both interceptor maneuverability and the total guidance and control system responsiveness are critical to the antiair application. Furthermore, flight tests and detailed simulation results to date on candidate-preferred orientation control configurations have not achieved total response times currently available with existing skid-to-turn control configurations. The dominant characteristic impacting the achievable response time is dynamic coupling among subsystems due primarily to nonzero interceptor body rotational rates and accelerations. Thus, this paper[1] was compiled to document the current status of autopilots for preferred orientation control, identify the critical autopilot and aerodynamic coupling paths and associated parameters, and identify issues that should be resolved before preferred orientation control autopilots are implemented in tactical antiair missiles.

Introduction

Manned aircraft have always used a form of preferred orientation control (POC), (i.e., bank-to-turn control) and only recently have configurations been developed which provide direct sideslip control (i.e., skid-to-turn) primarily to enhance responsiveness in air combat. On the other hand, antiair tactical missile technology has been dominated by skid-to-turn configurations, with only a recent renewed emphasis on exploring POC configurations. Basically, there are two reasons for this renewed interest for tactical missiles. First, the Navy has established two separate, distinct mission objectives that rely on the successful application of ramjet propulsion technology: 1) to provide for more missiles onboard each aircraft without sacrificing range or performance capabilities (i.e., enhance loadout characteristics), and 2) to provide long-range surface launch capability in support of the outer air battle.
Furthermore, the most efficient air inlet configurations satisfying both missions require POC for optimum performance. This is the principal motivation for the renewed interest in POC. The second reason for renewed interest in POC for tactical missiles is increased maneuverability via either the reduction in severity of aerodynamic roll-yaw coupling of symmetrical vehicles or via monoplanar configurations which provide enhanced lift without an attendant drag and weight penalty.

Analyses to date indicate that the successful application of POC control concepts to antiair tactical missiles will require favorable resolution of several critical issues associated with guidance and control during terminal homing, particularly for radio frequency (RF) systems. This type of control (i.e, POC) enhances the influence of existing dynamic coupling paths within the guidance and control systems and creates additional coupling paths due to the inherent nature of the vehicle motion required. These coupling paths alter the stability and control characteristics of the guidance and control systems and limit the applicability of existing skid-to-turn technology.

Considerable effort has been expended over the past few years in POC development for tactical missiles. The following pages summarize the status of POC autopilot technology for high-performance tactical antiair missiles and identify concerns with applying the new technology to near-term missile systems, as well as issues associated with the application of POC to terminal homing. POC guidance issues are beyond the scope of this paper, but will be addressed in one forthcoming.

Preferred Orientation Control Missile Programs

Before discussing POC technical issues, it is of interest to identify past and present programs and airframe configurations which either have or are seriously considering this type of control. Listed in Table 1 are missile programs[2] in which the autopilot design is relatively mature (i.e., includes actuator dynamics and nonlinearities, elastic body modes, and nonlinear cross-coupled aerodynamics). The Martin-Marietta Advanced Strategic Air Launched Multimission Missile (ASALM) has been successfully flown while Ramjet Interlab Air-to-Air Technology (RIAAT), a more advanced ASALM version (Martin-Marietta), and ASALM (McDonnell Douglas) incorporate autopilot designs which have been analyzed over the expected flight envelope but not flight tested. The Johns Hopkins University Applied Physics Laboratory (JHU/APL) Wide Area Guidance and Control (WAGC) program investigated three POC variants for applicability to the Navy's chin inlet long-range candidate missile configuration. The Naval Surface Weapons Center (NSWC) Surface Launched Weapons Aerodynamics and Structures Block program applied a modern control design technique to improve performance of a

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Table 1 Advanced level programs considered

Program	Mission	Contractor
Ramjet Interlab Air-to-Air Technology (RIATT)	Medium Range—Long Range (MR-LR) tactical air-to-air missile (AAM)	Hughes Aircraft, Canoga Park, Calif.
Advanced Strategic Air Launched Multi-mission Missile (ASALM)	LR, Strategic AAM and Air-to-Surface Missile (ASM)	McDonnell Douglas Astronautics, St. Louis, Mo. Martin-Marietta, Orlando, Fla.
Wide Area Guidance and Control (WAGC)	LR, Tactical Antiair	The Johns Hopkins University Applied Physics Laboratory (JHU/APL), Laurel, Md.
Surface Launched Weapons Aerodynamics and Structures Block	LR, Tactical Surface-to-Air Missile (SAM)	Naval Surface Weapons Center (NSWC)/Dahlgren, Va
NASA Advanced Missile Technology	LR, Tactical Antiair	JHU/APL
Guidance and Control for BTT Intercept Missiles (Independent R&D, IRAD)	LR, Tactical Antiair	McDonnell Douglas Astronautics, St. Louis, Mo.
Advanced Common Intercept Missile Demonstration (ACIMD)	MR-LR, Tactical AAM	Naval Weapons Center (NWC), China Lake, Calif.

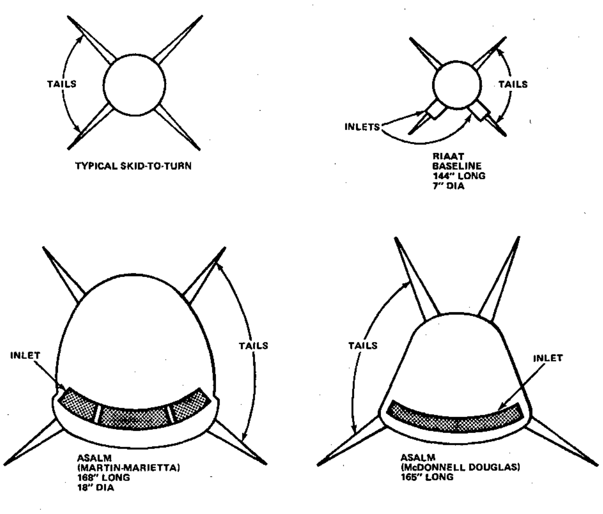

Fig. 1 Nonplanar aerodynamic configurations.

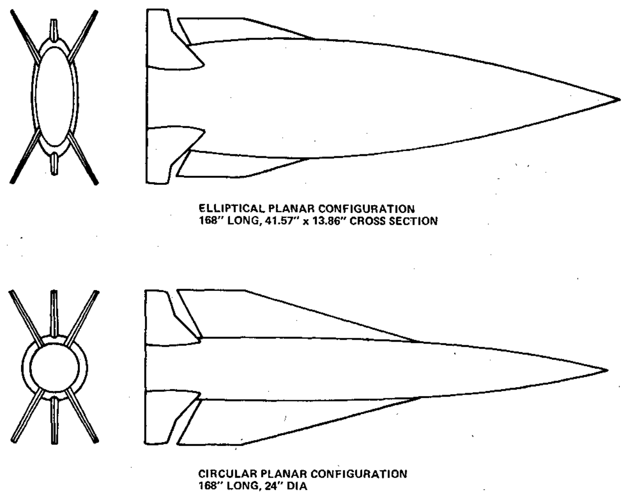

Fig. 2 NASA circular and elliptical planar configurations.

long-range tactical surface-to-air missile. NASA supported POC control system investigations[2] for their exploratory planar airframe configurations. The McDonnell Douglas IRAD program applies hybrid POC autopilot and optimal guidance techniques to improve tactical ramjet missile performance. Finally, the Advanced Common Intercept Missile Demonstration program is being conducted by the Naval Weapons Center, using hardware-in-the-loop simulation and limited flight testing, to demonstrate the use of POC for maximizing F-14 aircraft potential in the outer air battle.

Four nonplanar aerodynamic configurations are shown in cross section in Fig. 1. The typical rocket-propelled STT vehicle is axisymmetric with cruciform tails. The RIAAT baseline missile design uses a ducted rocket ramjet with two of the four cruciform tails located in line with the ducts. The Martin-Marietta ASALM has an integral rocket ramjet with an underslung chin inlet, circular fore body, and modified cruciform tails. The McDonnell Douglas ASALM also uses an integral rocket ramjet with an underslung chin inlet, but for purposes of high launcher efficiency has a modified trapezoidal body and more greatly altered tails. Figure 2 shows the circular and elliptical planar configurations designed by NASA and investigated by JHU/APL to identify desirable trends for aerodynamic coefficients. The elliptical configuration has a 3:1 cross section, while both have the same cross-sectional area distribution. Both configurations use four identical tail controls mounted in a ± 30-deg dihedral. The total span of the monowings is the same, requiring a larger wing area for the circular configuration. The planar configuration to be used by the Naval Surface Weapons Center ACIMD will use the planar configuration shown in Fig. 3. The missile is SPARROW size and uses an integral rocket ramjet with an underslung inlet. The configuration has two fixed wings and is controlled with four cruciform tails.

Table 2 provides a summary of the maneuver constraints for these POC missiles. These constraints dictate the choice of autopilot control. During midcourse flight, the ramjet missiles, RIAAT, ACIMD, and the two ASALM versions, require POC control to prevent missile maneuvers from shading the inlet (i.e., no negative α permitted) and to limit sideslip β in order to increase engine efficiency and thereby maximize range. During terminal flight, however, the RIAAT twin duct ramjet and the ACIMD integral rocket ramjet allow negative α and large transient sideslip (β) to occur. Although engine performance is sacrificed, it is expected that overall guidance system responsiveness and, ultimately, performance would be substantially improved. This is one of the technical issues to be resolved by the ACIMD flights. For the ASALM vehicles' terminal portion of the flight, engine operability was to be maintained. Since a flameout can occur if airflow is greatly restricted, constraints were placed on both α and β.

Many different POC control approaches are being considered as candidates for providing the required performance level while satisfying vehicle maneuver constraints. The constraint which is the most difficult to satisfy while maintaining satisfactory response times is that of allowing only positive angles of attack while maintaining small sideslip angles. Although during the midcourse phase of flight for tactical missions or for strategic missions response time is not a limitation, it is critical for the terminal homing portion of a tactical missile mission. The next section, in more detail will discuss the relationships among airframe, propulsion requirements, and maneuver constraints and the implication of these constraints on system responsiveness.

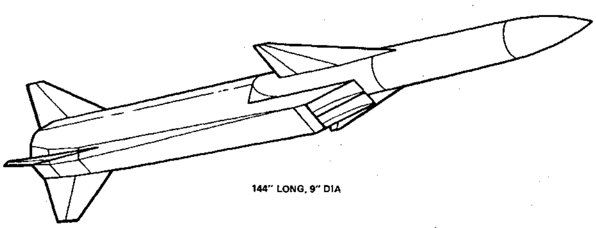

Fig. 3 ACIMD (Naval Weapons Center).

Missile Control Techniques

There have been a number of preferred orientation control concepts for tactical missiles explored over the past few years. This section will catalogue these concepts based on fundamental properties. Within each class of POC system, the principal applications will be identified. This section will provide first the definitions and nomenclature required, then a discussion of each class of POC system.

Figure 4 provides some angle definitions and nomenclature used to describe missile motion in the following discussions. A missile is shown flying in the direction indicated by the velocity vector $\vec{V}$ which forms the total angle of attack α_T with the major axis of the missile. The three-dimensional orientation of the missile body with respect to $\vec{V}$ is defined by the angle of attack α and angle of sideslip β. These angles are formed by the missile roll axis and the projections of $\vec{V}$ on the pitch and yaw control planes. The angle that the pitch direction makes with the inertial reference is the roll angle ϕ.

A two-dimensional representation of missile orientation is used in Fig. 5 to show the constraints in α and β for each class of control policy. The magnitude of α is shown along the body-fixed pitch axis and the magnitude of β is shown along the body-fixed yaw axis. The grey regions show the allowable α and β values for each control system.

Table 2 Selected missile airframes and maneuver constraints

Airframe	Guidance mode	Constraint	Reason
RIATT (Ducted-Rocket Ramjet)	Midcourse	Positive angle of attack (α) only with small allowable sideslip (β) levels	Engine efficiency
	Terminal	Small allowable steady-state sideslip	Speed of response Engine efficiency
		No roll motion at low acceleration levels	Guidance noise Radome boresight errors
ASALM (Integral Rocket Ramjet)	Midcourse	Positive α Small β	Engine efficiency
MDAC-E & M-M	Terminal	$-5° \leq \beta \leq 5°$ $-5° \leq \alpha \leq K^{a}$ and Positive α	To prevent flameout
Typical Skid-to-Turn	Midcourse and Terminal	$-K \leq \alpha \leq K$ $-K \leq \beta \leq K$	Proven technology for antiair tactical missiles
NASA Experimental Vehicles	Terminal	Positive α Small β	Maneuverability Aerodynamic cross-coupling
ACIMD (Integral Rocket Ramjet)	Midcourse	Positive α Small β	Engine Efficiency
	Terminal	$-K \leq \alpha \leq K$ Small allowable steady-state sideslip	Maneuverability Aerodynamic cross-coupling Speed of response Reduced slowdown

[a] K indicates a large angle.

From a controls viewpoint, POC systems can be subdivided based on the constraints placed on α and β. These constraints in turn define the requirements for the control of the roll angle ϕ. There are four fundamentally different types of control illustrated in Fig. 5, denoted Classes A through D, of which only three would be considered POC systems. The illustration in the upper left corner (i.e., Class A) is an example of skid-to-turn control. Maneuverability is achieved by developing the appropriate angle-of-attack and sideslip angle simultaneously while maintaining the roll angle fixed with respect to inertial space. The cloverleaf pattern results from the fact that aerodynamic coupling and control surface effectiveness vary with respect to airframe maneuver direction.

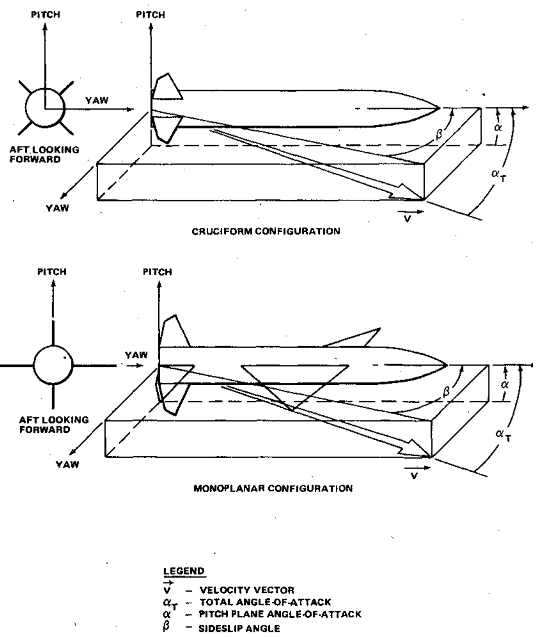

Fig. 4 Definition of angles for cruciform and monoplanar missile configurations.

In the lower left corner (i.e., Class B) is one of the POC configurations. For some cruciform configurations, the maneuverability in some directions is substantially less than others due to aerodynamic cross-coupling or control surface effectiveness. In this situation, the maneuverability of the round can be enhanced by controlling the roll angle ϕ such that $|\alpha|$ and $|\beta|$ are not large, simultaneously. A characteristic of this type of control is that any change in maneuver direction would require, at most, a roll angle change of 45 deg.

Another class of preferred orientation control is shown in the upper right corner of Fig. 5 (i.e., Class C). This type of system restricts the allowable level of sideslip and would be used with a monoplanar and/or a dual inlet ramjet configuration as illustrated. This concept may also be used with a single inlet configuration if blocking the inlet is not objectionable and response time is of concern. With this system, a change in maneuver level requires, at most, a 90-deg change in roll orientation.

The final class of preferred orientation control and one that is the most challenging from the standpoint of achieving a given responsiveness is shown in the lower right corner of Fig. 5 (i.e., Class D). Here both $|\beta|$ and negative α are restricted to be small. The roll angle may have to be changed by 180 deg to respond to a given maneuver change which can result in high roll rates and significant cross-coupling among control channels. This is the classical bank-to-turn control policy.

There are many autopilot command logic options for achieving the three classes of POC control systems shown in Fig. 5. The options result in different missile motion for the same class of POC system. Table 3 shows current autopilot command logic options, their corresponding classification, and terminology. The options consist of two basic types, those which have Cartesian commands (i.e., pitch and yaw autopilot channels are commanded) shown in the upper part of the table and those which have polar commands (i.e., pitch and roll autopilot channels are commanded) in the lower part of the table. The names given to the command logic are descriptive of the type of resulting missile motion (e.g., skid-to-turn, roll-during-turn, twist-and-steer, bank-to-turn), allowable magnitude of roll angle change (e.g., unlimited, limited), and degree of sideslip control (e.g., coordinated).

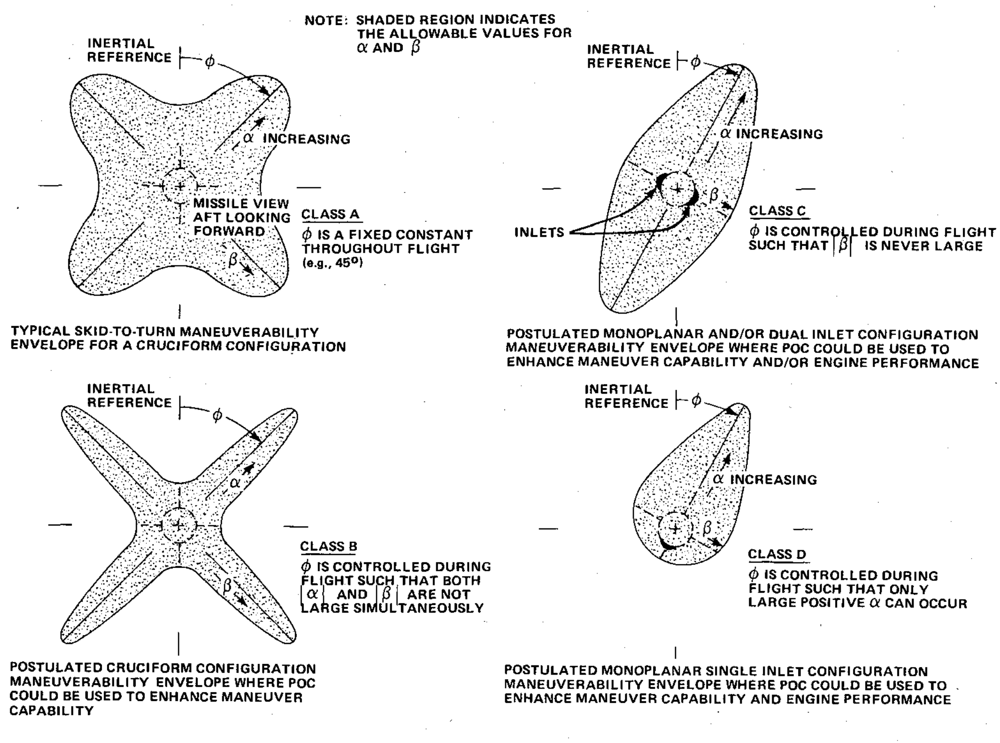

Fig. 5 Types of missile control and constraints.

Table 3 Autopilot command logic options

Classification	Pitch	Yaw	Roll	Terminology
A	Guidance commands $\pm\alpha$	Guidance commands $\pm\beta$	Angle fixed in inertial space, $\phi=0$	Skid-to-Turn (STT)
B and C	Guidance commands $\pm\alpha$	Guidance commands $\pm\beta$	Guidance commands maximum angle changes of ± 45 deg, ± 90 deg Guidance commands only at small α, β	Roll-During-Turn (RDT) Limited-RDT (LRDT) Twist-and-Steer (TAS)
C	Guidance commands $\pm\alpha$	Guidance commands $\pm\beta$ limited to aid coordination	Commanded by autopilot measurements for coordination	Coordinated RDT (CRDT)
B and C	Guidance commands $\pm\alpha$	Commanded by autopilot measurements for coordination	Guidance commands maximum angle changes of ± 45 deg, ± 90 deg	Limited Bank-to-Turn (LBTT) Limited Coordinated BTT (LCBTT)
D	Guidance commands $+\alpha$	Commanded by autopilot measurements for coordination	Guidance commands maximum angle changes of ± 180 deg Guidance commands only at small α, β	Bank-to-Turn (BTT) Unlimited BTT (UBTT) Coordinated BTT (CBTT) Unlimited CBTT (UCBTT) Twist-and-Steer (TAS)

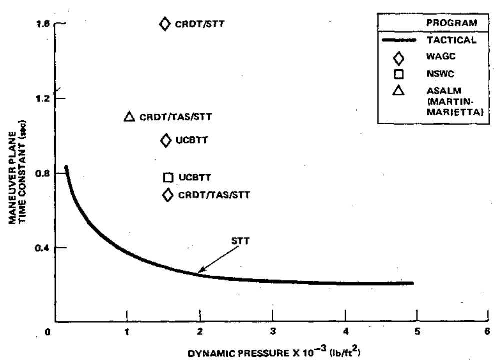

Fig. 6 Worst-case maneuver (180 deg roll to commanded acceleration).

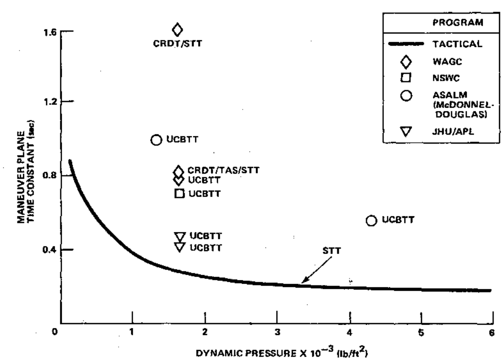

Fig. 7 180 deg change in acceleration command.

Command logic options in Table 3 have been combined into hybrid POC systems. One combination, STT and LRDT, uses STT at low α_T to reduce the effects of bias, noise, and radome boresight errors of POC. TAS has been combined with CRDT to produce a resultant Class D control system.

POC Response Time

For most practical tactical missile designs, maneuvers are realized by developing the appropriate angle of attack. At low dynamic pressure, quite large angles of attack are frequently necessary to achieve the required maneuver levels. For POC systems, not only must the airframe rotate to develop the appropriate angle of attack, but also it must be rolled appropriately to satisfy sideslip constraints. The most difficult maneuver for a given response requirement in a POC system is the 180-deg roll in conjunction with an angle-of-attack change. This worst-case maneuver response time is indicated for various missiles and control systems in Fig. 6, along with typical skid-to-turn results. These data demonstrate the sluggishness of current POC systems compared to skid-to-turn. These data also indicate that response time is related to the particular POC control policy employed.

A POC autopilot can theoretically respond more rapidly than STT at low dynamic pressures. The POC response is determined by the roll channel response which theoretically can be considerably faster than the steering channel response. Figure 7 shows the response of ramjet missiles when forced to roll 180 deg (worst-case maneuver) and the acceleration is at or near the desired level. The small improvement of WAGC UCBTT is limited by its slow roll channel response, while the response of WAGC CRDT/TAS/STT is slower because of the dependence on STT steering channels. The strategic ASALM UCBTT responses shown can be improved by blending LCBTT with STT in the terminal mode to improve response, roll jitter, and radome boresight error effects. JHU/APL UCBTT and the NSWC UCBTT responses revealed coupling effects which slowed responses and resulted in over and undershoots. These coupling effects will increase with attempts at more rapid response times.

POC response for autopilots with a preferred maneuver plane (maximum roll of 90 deg with no negative angle-of-attack constraints) is shown in Fig. 8. These autopilots may respond almost as rapidly as STT depending on roll channel response. The RIAAT LRDT/STT baseline control system, however, has a conservative response. Hughes is studying a planar vehicle for improved performance at low dynamic pressures.

The test results indicated in Figs. 6-8 show that it has not been demonstrated that a POC autopilot can achieve response times currently available with skid-to-turn tactical missiles. More rapid response times, however, reveal coupling effects which raise critical design issues.

POC Critical Control Issues

Missile dynamics have inertial and kinematic cross-coupling between pitch, yaw, and roll channels which is more severe with increasing missile roll rate and with asymmetrical airframes. The effects on the conservative POC autopilot designs presented here have been to increase response time and/or introduce transients in the maneuver plane acceleration response in the form of over and undershoots.[1] Aerodynamic control cross-coupling is more critical when the control system uses coordination techniques.[3] Coordination difficulties increase with large angles of attack and roll rates which require larger bandwidths for the coordination channel. These bandwidths, in turn, are limited by actuator capability

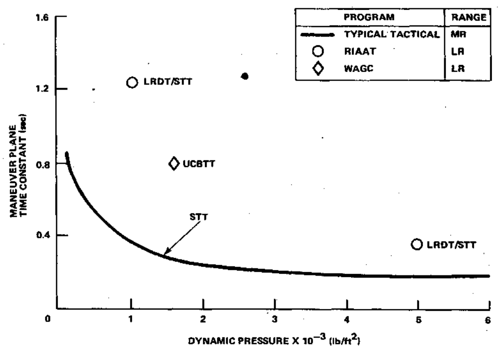

Fig. 8 Worst-case maneuver (90 deg roll to commanded acceleration).

and the required attenuation at missile body elastic modes. The maneuver constraint of one preferred maneuver direction (no negative α) calls for even more greatly increased roll rates which intensify coupling and coordination problems.

Channel Coupling in Symmetrical Cruciform Missiles

The channel coupling for cruciform (or very near cruciform) missiles due to missile roll rate and coordination is shown via dashed lines in Fig. 9. The figure illustrates the kinematic and inertial cross-coupling between pitch and yaw channels. Kinematic cross-coupling becomes more severe with increasing angle of attack[4] and/or sideslip. Inertial cross-coupling becomes more severe with increasing missile steering angular rates. These couplings are all multiplied by roll rate and therefore become more severe with increasing roll rate. Because roll rates are low for STT missiles during the terminal phase of flight, inertial cross-couplings have negligible influence on autopilot stability or missile performance. For POC control using large missile roll rates, these couplings can no longer be neglected.

The coordination command, used by UCBTT and LCBTT and shown entering the yaw control, forms a feedback loop through the yaw channel into the roll channel through the control surface coupling, and then back to the coordination command. This results in a relative stability problem in the coordination command branch which increases the importance of reducing the effect of yaw tail incidence to induced roll moment.

Channel Coupling in Asymmetrical Airframes

Added to the kinematic and inertial coupling of the axisymmetrical cruciform airframe is additional inertial coupling due to airframe asymmetry. This additional effect caused by two planes in the missile having different geometric and mass symmetry, couples the product of pitch and yaw angular rates into the roll angular acceleration as shown in Fig. 10. This coupling is not dependent on the magnitude of missile roll rate.

An additional inertial coupling, resulting in coupling paths dependent upon roll rates, occurs when the airframe has geometric and mass symmetry in one plane. The square of roll

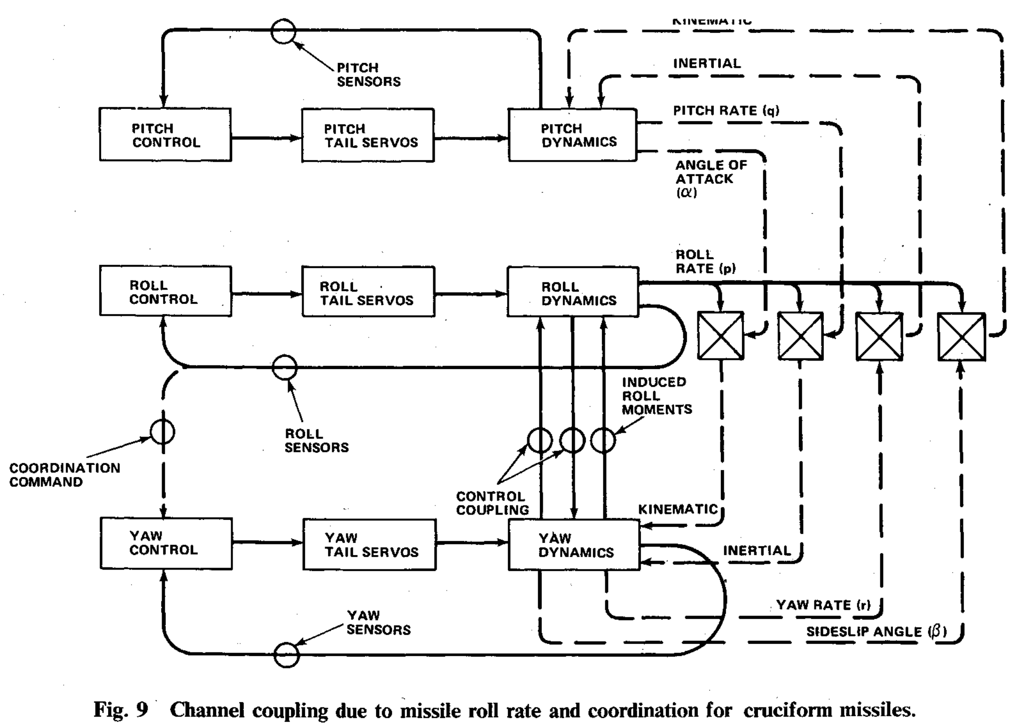

Fig. 9 Channel coupling due to missile roll rate and coordination for cruciform missiles.

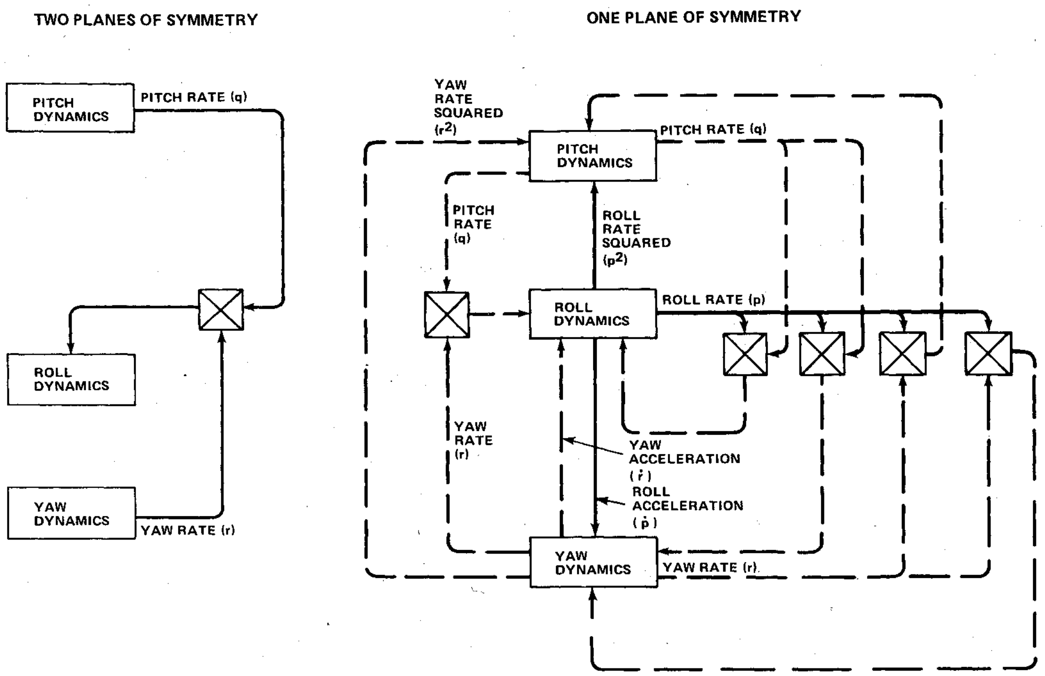

Fig. 10 Additional inertial coupling due to airframe asymmetry.

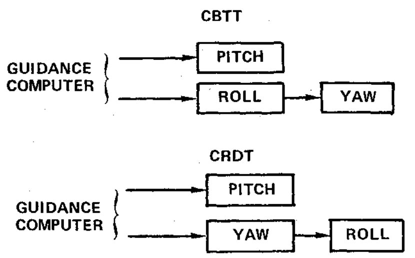

Fig. 11 Autopilot architectures of classical designs.

rate and the product of roll and yaw angular rates are coupled into pitch angular acceleration. Roll angular acceleration and the products of roll and pitch and also roll and yaw angular rates are coupled into yaw angular acceleration. In addition, the product of roll and pitch angular rates is coupled into roll angular acceleration.

Critical Control Issues of Current Classical Designs

The architecture of the classical design of a CBTT autopilot is shown in Fig. 11. When commanding a missile to roll 180 deg to a desired acceleration level, the roll channel must respond faster than the pitch channel for the maneuver plane response to be as fast as STT.[5] For satisfactory coordination, the yaw channel following the roll channel must respond faster than the roll channel and therefore faster than the pitch channel. This is difficult to accomplish since missile yaw inertia is larger than roll inertia and comparable to pitch inertia. Actuator capability and attenuation at missile elastic body modes are the limiting factors in channel response.

The architecture of the classical design of a CRDT autopilot is shown in Fig. 11. The guidance computer commands the pitch and yaw channels, while the roll channel follows the yaw channel for coordination. To prevent negative angles of attack for one preferred maneuver direction, TAS control has been applied to the ASALM CRDT autopilot. Fast speeds of response are limited because CRDT and TAS operate in series with each other, thus adding the respective time constants.

Near-Term Applicability of POC to Tactical Missiles

In situations where speed of response is not a critical issue (e.g., midcourse guidance) POC technology is well advanced and has been demonstrated with a chin inlet ramjet. For terminal flight, however, the tactical missile response times for acceleration in the desired maneuver plane have not been demonstrated to date and there are many unresolved critical control issues in POC systems. Even more critical are the guidance issues which are beyond the scope of this paper.

Remaining Issues Associated with the Applicability of POC to Antiair Tactical Missiles

The development of POC systems for tactical missile control, particularly during terminal homing, may require investigations in the following areas:

1) Airframe Design. Airframe designs are desirable which have the potential for improved POC performance. One approach to achieving such a design is by considering both aerodynamic and autopilot design goals simultaneously. Reference 3 represents an initial effort directed at such a goal. This preliminary data does indicate a significant payoff may be achieved by such an approach.

2) POC Autopilot Design and Verification. Due to the significant effect nonlinear cross-coupled missile dynamics have on response characteristics, the POC autopilot will require design procedures capable of dealing with these effects and considerably more verification studies than are required for roll-stabilized STT autopilots. A range of dynamic pressures should be considered since low dynamic pressures and large angles of attack will make sideslip control more difficult, whereas high dynamic pressures which are accompanied by more rapid response will increase the severity of inertial cross-coupling. Satisfactory response of maneuver plane acceleration for worst-case maneuver directions and range of acceleration levels should be demonstrated. Satisfactory relative stability in critical autopilot branches and sensitivity of aerodynamic cross-coupling should be demonstrated for flight conditions of interest (i.e., Mach, altitude, and time are fixed).

Conclusions

All types of BTT missile autopilots (control classes B through D, Fig. 5) will now satisfy guidance system requirements of advanced level programs where rapid speeds of acceleration response are not required. Tactical speeds of acceleration response during the terminal phase may not be achieved by bank-to-turn autopilots due to kinematic and inertial coupling. This coupling is shown to increase in severity with more rapid missile roll rates and increasing airframe asymmetry as the control class changes from B towards D. Therefore, improved maneuverability of asymmetrical BTT airframes may be achieved at the expense of speed of acceleration response. Development of BTT autopilots for tactical missiles during terminal homing may require the use of class B or C control to decrease the severity of coupling. Integrating BTT airframe design and improved autopilot design procedures may also be required to deal with the nonlinear cross-coupled BTT dynamics.

Acknowledgment

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