FULL LENGTH PAPER

EFFECT OF FLEXIBILITY AND AIRCRAFT FLOW FIELD ON RAIL LAUNCH SIMULATION OF A MISSILE

Shaik Ismail; P. C. Jain; P. S. R. Anjaneyulu
Scientist
Defence Research and Development Laboratory (DRDL)
Kanchanbagh Post,Hyderabad-500 058, India
Email : jainpcj@yahoo.com

Abstract

One of the major causes for the dispersion of missile trajectory is its tip-off from the launcher. Generally low fidelity models are used to predict the tip-off of a missile. One or the other important parameters, like flexibility of missile, flexibility of launcher rail, clearances between launch shoes of missile and launcher rail are omitted in these low fidelity models. In the present study, effects of missile and launcher flexibility on missile tip-off are studied by comparing the results by a low fidelity rigid body simulation model and a 3D finite element model. Predicted tip-off by these two models is compared with ground flight measured data. Effect of omitting one of the launch shoes on missile tip-off is also studied using low fidelity model. For a ground launched missile gravitational pull decides the missile tip-off, but for aircraft launched missiles, aircraft flow field is equally important. Rail phase of an air to air missile is simulated considering varying aircraft flow field, using a full-fledged 3D Finite Element Model.

Nomenclature

$[C]$ = Structural Damping Matrix
F_N = Contact Normal Force
$\{F^a\}$ = Applied load vector
K = Material stiffness
$[K]$ = Structural Stiffness Matrix
$[M]$ = Structural Mass Matrix
n = Force exponent
$\{u\}$ = Nodal displacement vector
$\{u'\}$ = Nodal velocity vector
$\{u''\}$ = Nodal acceleration vector
δ = Penalty or amount of penetration

Introduction

Launchers of missiles are broadly classified as rail and ejection launchers. Generally missiles which are smaller in diameter (less than seven inches), lighter in weight (less than 350 pounds) and having high initial axial acceleration (higher than 10 g) are released from a rail launcher [1]. A rail launched missile is the one which travels along the rails of the launcher by self-propulsion system, typically solid propulsion system. Time varying thrust propels the missile during rail phase. A ground launched missile will tilt downward under the influence of gravity and cause the missile to fly a new flight path [2]. For ground launch missiles modeling the dynamics of missile and launcher captures the tip-off accurately [3] [4]. For air launched missiles prediction of aerodynamic data on missile due to aircraft flow field is equally important. For ejection launched missiles, commercial software like Zeus Numeric predicts the tip-off by integrating the CFD simulations with 6-DOF dynamics solver. This approach of integrating CFD code with 6-DOF dynamic solver is tried for rail launched air to air missile [5]. But the 6-dof solver used works on point support model, predicts only pitch rate, doesnt predict roll and yaw rates. In the present work, the shortcomings of 6-dof dynamic solver used in the previous work [5] are addressed by simulating the rail phase of air to air missile by carrying out transient dynamic analysis with aircraft flow field as excitation force. Clearances between rail and launch shoes on missile are modeled in 3D Finite Element model of rail and missile to capture all three angular rates of missile during rail phase. These clearances results in rapidly varying contacts be-

Paper Code : V68 N2/902-2016. Manuscript received on 04 Mar 2015. Reviewed, revised and accepted as a Full Length Contributed Paper on 22 Mar 2016

tween rail and launch shoes. Unique features of the present work are :

- Simulation of rail phase by considering the clearances, between rail and launch shoes on missile. This captures pitch rate of missile from the beginning of rail phase if any, whereas the previous work [5] predicts tip-off only after the first shoe leaves the rail.
- Comparison of flight measured tip-off data for a ground launched missile with a low fidelity rigid body simulation and flex body simulation.
- An integrated approach, to simulate rail phase of an air launched missile by combining successive quasi steady CFD simulations with nonlinear transient dynamic analysis.
- Identification of parameters affecting motion of an air launched missile in different directions.

Tip-off Prediction by Low Fidelity Model

One of the low fidelity models widely used in predicting missile tip-off is 'Rigid Body Simulation'. In this model both the missile and launcher rail are considered as rigid bodies. Tip-off for a missile launched from ground is predicted using this low fidelity model.

The ground launched missile considered in the present work has three launch shoes and the C.G of the missile is ahead of the first launch shoe. Initiation of solid rocket motor of the missile releases the detent mechanism holding the missile, and missile starts moving. Clearances are provided between launcher rail and missile launch shoes for integration purpose. These clearances are of the order of 2 mm, modeled in CAD software and exported to carry out rigid body simulation. Schematic of missile and the arrangement of launch shoes in the rail are shown in Fig.1.

Rail phase of the missile launched from ground is simulated by carrying out rigid body simulation using commercial software by Msc, ADAMS/AVIEW. Time varying thrust is modeled using AKISPL SPLINE function of ADAMS as shown in Fig.2.

Missile and launcher are modeled as rigid bodies simulating mass, C.G. and mass moment of inertias. Contact between launch shoes and rail is defined using inbuilt IMPACT function of ADAMS. The IMPACT function activates when the two parts collide. When the two parts penetrate a normal force $F_N=K\ \delta^n$ will be applied to separate them apart. Gravitational force is considered for the analysis. GSTIFF solver with a time step of 0.001s is used for carrying out the analysis. Analysis is carried out until the third shoe of the missile leaves the launch rail.

As the C.G of missile is ahead of first launch shoe, it experiences a pitch down movement resulting in buildup of pitch angular rate from beginning. Pitch angular rate increases until the third launch shoe touches the top of the rail, after that missile starts pitching up. This phenomenon is captured by simulation as shown in Fig.3.

To understand the effect of second and third launch shoes on pitch rate, rigid body simulation is carried out with and without second and third launch shoes and the resulting pitch rate is compared in Fig.4 and 5.

By omitting third launch shoe, missile has less pitch rate compared to three shoe configuration. But the rear of the missile collides with launch rail, as second shoe is located much ahead of end station of missile. Although rigid body simulation provides some insight to the launch phenomenon, it doesn't capture the structural dynamics aspect as both rail and missile are elastic metallic structures. Hence transient dynamic analysis by modeling the gaps between rail and shoes is carried out in ANSYS considering the flexibility of missile and rail.

Tip-off Prediction by 3D Finite Element Model

Rail phase of the missile is simulated in ANSYS by carrying out transient dynamic analysis. Previous works on rail launch simulation, models the missile and rail with simplified beam and shell elements [6] [7], as the emphasis is on reduction in disc storage and computational time. Transient analysis with 3D Finite elements and contact elements between rail and launch shoes is attempted in the present work. A transient structural analysis can be either linear or nonlinear. In the present study the nonlinearity is due to changing contact status between launch shoes and rail as missile travels along. Airframe of missile is modeled with SOLID 73 elements of ANSYS. It is eight noded pseudo-solid brick element having six degrees of freedom. Finite element model of the missile along with the rail is shown in Fig.6.

Rail and launch shoes are modeled with hex dominant mesh and other elements of missile like bulkheads, wings and fins are modeled with tetrahedral elements of solid 73. This method of having both regular hex mesh and irregular tetra mesh greatly reduces the number of elements and there by computational time. Finite element model contains around one million elements. Articles other than airframe are modeled with Mass 21 elements of ANSYS. Mass elements which are placed inside the missile are connected to airframe by node coupling technique as shown in Fig.7. Clearances between rail and launch shoes are modeled. TARGET 170 and CONTA 174 elements of ANSYS are used to model the contact between rail and shoes as shown in Fig.8.Coulomb friction model is used for defining the contacts. Surface to surface contact with flexible target has been defined between rail and shoes. Rail is defined as target surface and launch shoe surfaces are meshed with contact elements. Augmented -Lagrangian method is used as contact algorithm.

The purpose of a transient response analysis is to compute the behavior of a structure subjected to time-varying excitation. For the present work, as missile travels along the rail, the contact status of launch shoes with rail changes due to clearances. Direct integration method is used for the present analysis.

The equation of equilibrium for transient dynamic analysis is given in Eqn.(1).

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F^{a}\} \qquad (1)$$

An implicit scheme based on Newmark average acceleration method with integration time step of 0.002 s is used for carrying out transient analysis. Integration time step is chosen as 1/20th of first natural period of missile. Contacts between rail and launch shoes changes rapidly during solution process. Hence number of sub steps within each time step are made program dependent to achieve force convergence criterion. Stiffness proportional damping is used in the simulation. Time varying thrust force and constant gravitational pull are excitation forces for ground launch simulation. Transient analysis is carried out until the third shoe leaves the rail. Time at which first, second and third launch shoes leave the rail from rigid body simulation is compared to that of transient analysis results, and the results match within acceptable limits of 2 ms time difference.

The accelerometers of flight navigation system sense the acceleration of missile. Speed of missile is derived from the measured acceleration. Missile speed from the simulation is compared with flight measured speed and shown in Fig.9.As the third shoe leaves the rail, speed of the missile is around 20 m/s, good match is observed between measured missile speed and simulation.

Angular pitch rate from the transient dynamic analysis is compared with flight measured data and results from low fidelity rigid body simulation. The C.G. of missile is ahead of first launch shoe, missile experiences pitching down moment from the beginning of rail phase. This results in lifting of third launch shoe and hitting the top of the rail. Pitch rate of the missile changes sign as third shoe collides with top of rail. Both rigid and flex body simulations match with flight data, where pitch rate changes sign, at Zone A as shown in Fig.10.

Pitch rate at Zone B (Fig.10) is when the third shoe leaves the rail, pitch rate prediction by rigid body and flex body simulation are closer to flight data. Between Zone A and Zone B pitch rate prediction by flex body simulation is closer to flight data.

Rail Launch Simulation for an Air to Air Missile

A typical air to air missile launched from fighter aircraft is considered for the study as shown in Fig.11. This missile also has three launch shoes. Clearances between the rail and the launch shoes are similar to that of ground launched missile.

A typical launch case of missile release from non-maneuvering aircraft is considered. For this particular launch case, aerodynamic data on missile as a function of missile position is extracted by CFD studies using grid free Euler solver similar to the procedure discussed in [5]. Missile is placed successively at different locations along the length of the rail and aerodynamic forces and moments on missile in the presence of aircraft are extracted. All the three forces and three moments are considered for the analysis. Pitching moment and yawing moment are simulated as lateral forces acting on missile. Rolling moment is simulated by applying point forces on wings and fins of missile. Variation of forces acting on missile as a function of missile travel along the rail is shown in Fig.12.

Time varying thrust force and constant gravitational pull are considered for the analysis. For the particular launch condition considered in this analysis, aircraft releases the missile, as it is moving at constant velocity. Hence missile experiences constant gravitational acceleration of ‘1g’.

The problem has nonlinearity in two folds. Aero forces are function of missile displacement, hence nonlinearity, and the second nonlinearity is due to changing contact status between launch shoes and rail. Convergence during the time steps in which contact status changes rapidly like shoes leaving the rail is achieved by making number of sub steps as program dependent. Selecting Augmented-Lagrangian method also helped to achieve convergence as this method doesn't require contact stiffness. The drawback of this method is that contact forces can't be estimated directly. Force convergence criterion of residual force in a time step to be 0.1% of applied load in the next time step is imposed during the entire solution process. As Newmark's is an implicit scheme convergence is independent of time step and accuracy is of the order of square of chosen time step. After the convergence of each time step, aerodynamic forces and moments on missile are varied for the next time step, as a function of missile travel.

To understand the effect of aircraft flow field, transient dynamic analysis is repeated without aerodynamic force. Displacements of missile nose tip at the end of rail phase are compared with and without aircraft flow field and given in Table-1. Effect of Air craft flow field on the angular rates of the missile is shown in Fig.13 by plotting the missile Roll angular rate with and without Aircraft flow field.

Conclusions

Methodology for predicting the missile tip-off data using a 3D Finite element model by considering important parameters like, missile and launcher flexibility, aircraft flow field is discussed. Results from the 3D Finite Element Model are compared with a low fidelity model and flight measured data.

Table-1 : Comparison of Missile Nose Tip Displacement with and without Aero Load

	Without Aero Load	With Aero Load
Nose down displacement	35 mm	- 1.8 mm
Side-ways displacement	- 1.4 mm	59 mm
Duration of rail phase		0.192 s (Without flow)
		0.194 s (With flow)
Negative sideways displacement indicates missile is moving towards aircraft		

The following observations are made from the study.

- Tip-off prediction by low fidelity model (rigid body model) and by 3D FEM analysis is compared with flight measured data (Fig.10) for a typical ground launched missile. It is observed that transients during rail travel are well captured in FEM analysis compared to that of rigid body simulation. Based on this study, tip-off prediction by 3D EM analysis is adopted for an aircraft launched missile where safety of launching aircraft is important.
- Lateral motion of missile is governed by i) clearances between launcher to missile launch shoes ii)gravitational pull iii) aircraft flow field.
- Axial motion of the missile is influenced by time varying thrust force for a missile released from non-maneuvering Aircraft.
- Effect of aircraft flow field is presented in Table-1. Missile has a tendency to move away from aircraft (sideways movement of 54 mm) in the presence of aircraft flow field and has minimum sideways movement in the absence of aircraft flow field. This is important parameter for the safety of launching aircraft.
- Prediction of roll rate considering aircraft flow field matches well with flight measured data (Fig.13). Predicted maximum roll during missile travel in rail is -31 deg/s and flight observed maximum roll rate is -32 deg/s. In the absence of aircraft flow field maximum roll rate 7 deg/s for a typical aircraft launched missile.

Acknowledgement

The authors are thankful to Director and Project Director, Defence Research and Development Laboratory (DRDL), Hyderabad for interaction, review and valuable suggestions. We are grateful to Director, DOCD for providing required input.

References

1. Eugene L. FleemaN., "Technologies for Future Precision Strike Missile Systems - Missile/Aircraft Integration", RTO SCI Lecture Series held in Atlanta, USA, March 23-24, 2000.

2. Khalil, M., Abdalla, H. and Kamal, O., "Trajectory Prediction for Typical Fin Stabilized Artillery", Proceedings of 13th International Conference on Aero-

space Sciences and Aviation Technology, ASAT-13, May 26-28, 2009.

3. Yujun Chen and Yi Jiang., "Dynamic Design Technology of Missile Launch Systems", International Symposium on Information Engineering and Electronic Commerce, 3rd (IEEC 2011), July 22-24, Huangshi, China.

4. Zbigniew Koruba, et al., "Dynamics of a Controlled Anti-aircraft Missile Launcher Mounted on a Moveable Bas", Journal of Theoretical and Applied Mechanics, Vol.48, No.2, Warsaw 2010, pp.279-295.

5. Anandhanarayanan, K., Konark Arora., Vibhav Shah., Krishnamurthy, R. and Debasis Chakraborty., "Separation Dynamics of Air-to-Air Missile Using Grid Free Euler Solver", Journal of Aircraft, Vol.50, No.3, 2013, pp.725-731.

6. Peter Zeman., "Rail lAunch Missile Simulation Using MSC Nastran Software", Paper 2001-34, MSC World Wide Aerospace Conference-Part I, 2002.

7. Rhett Shaw and Mark Gillcrist., "Near-miss Shock Response of an Encanistered Vertical Launch Antisubmarine Rocket Carrying a MK54 Torpedo" Journal of Critical Technologies in Shock and Vibration, Vol.2, 2003, pp.1-15.

8. Hans Wallenius and Anders Lindberg., "Major Improvements in Store Separation Analysis Using Flexible Aircraft", 27th International Congress of the Aeronautical Sciences, ICAS 2010, September 19-24, Nice, France.

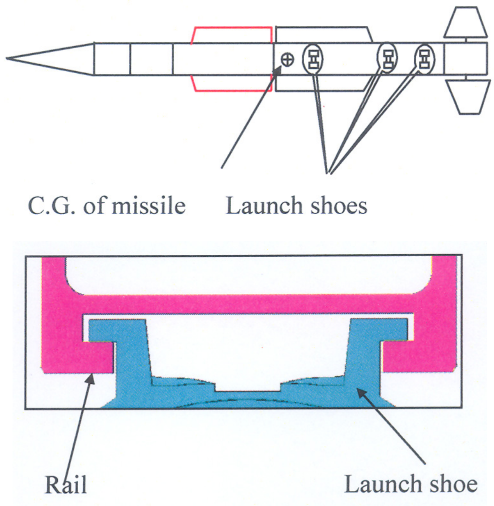


Fig.1 Missile with Three Launch Shoes and Clearances Between Rail and Launch Shoes

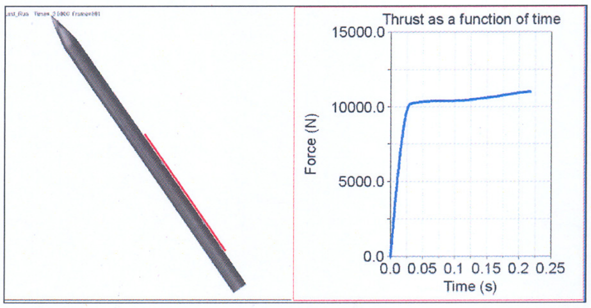


Fig.2 ADAMS Model and Variation of Thrust with Time

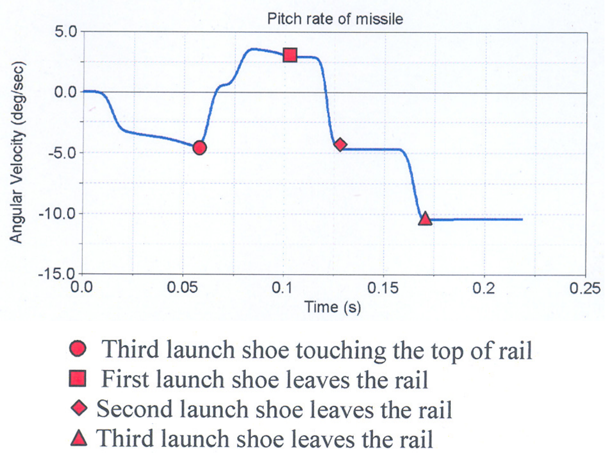


Fig.3 Variation of Pitch Angular Rate During Rail Phase

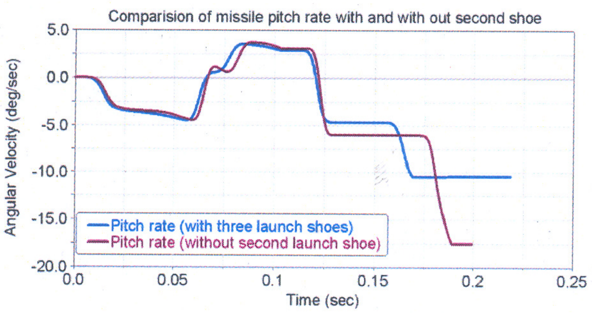


Fig.4 Comparison of Pitch Rate with and without Second Launch Shoe

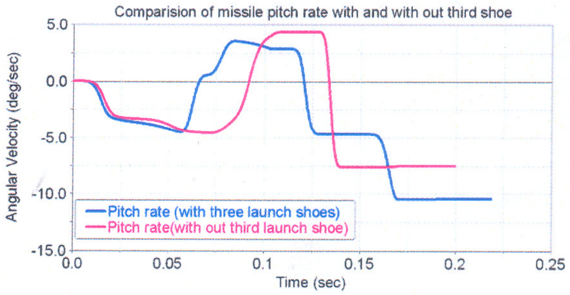


Fig.5 Comparison of Pitch Rate with and without Third Launch Shoe

Fig.6 3D Finite Element Model of Ground Launched Missile

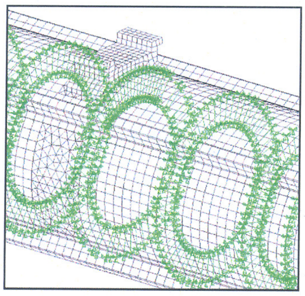


Fig.7 Finite Element Model of Missile and Rail

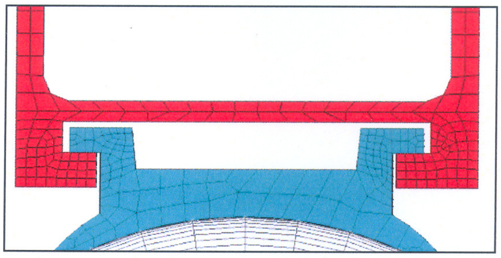
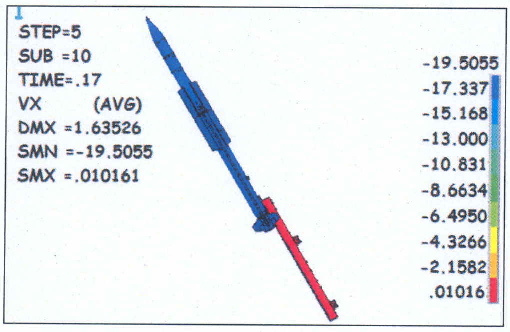


Fig.8 Contact Elements are Used to Define the Clearance Between Rail and Launch Shoe



Axial velocity contour

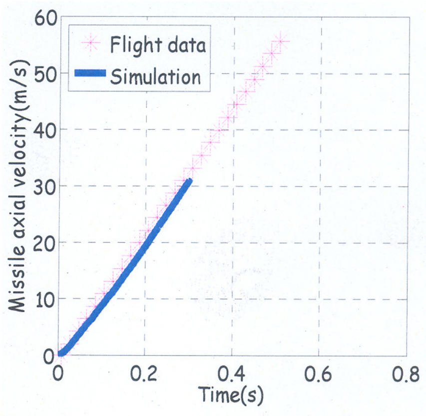


Fig.9 Comparison of Flight Measured Missile Speed with Simulation

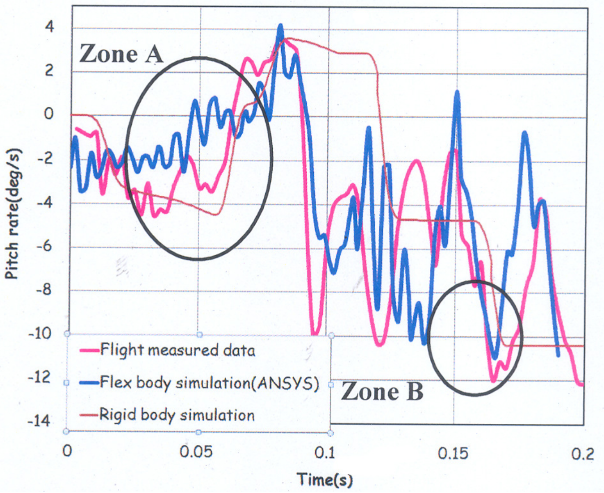


Fig.10 Comparison of Flight Measured Pitch Rate with Rigid Body Simulation and Flex Body Simulation Result

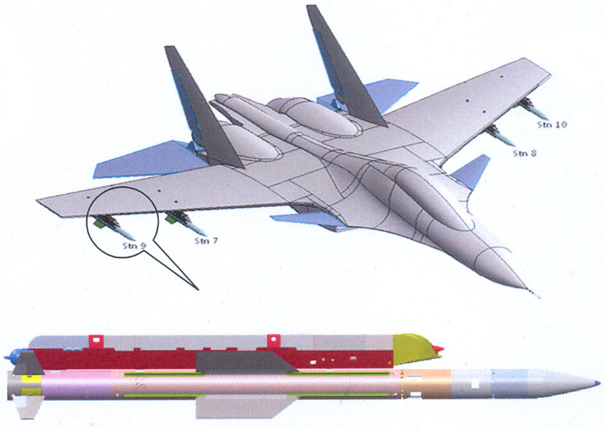


Fig.11 Air to Air Missile Attached to Four Stations of a Fighter Aircraft

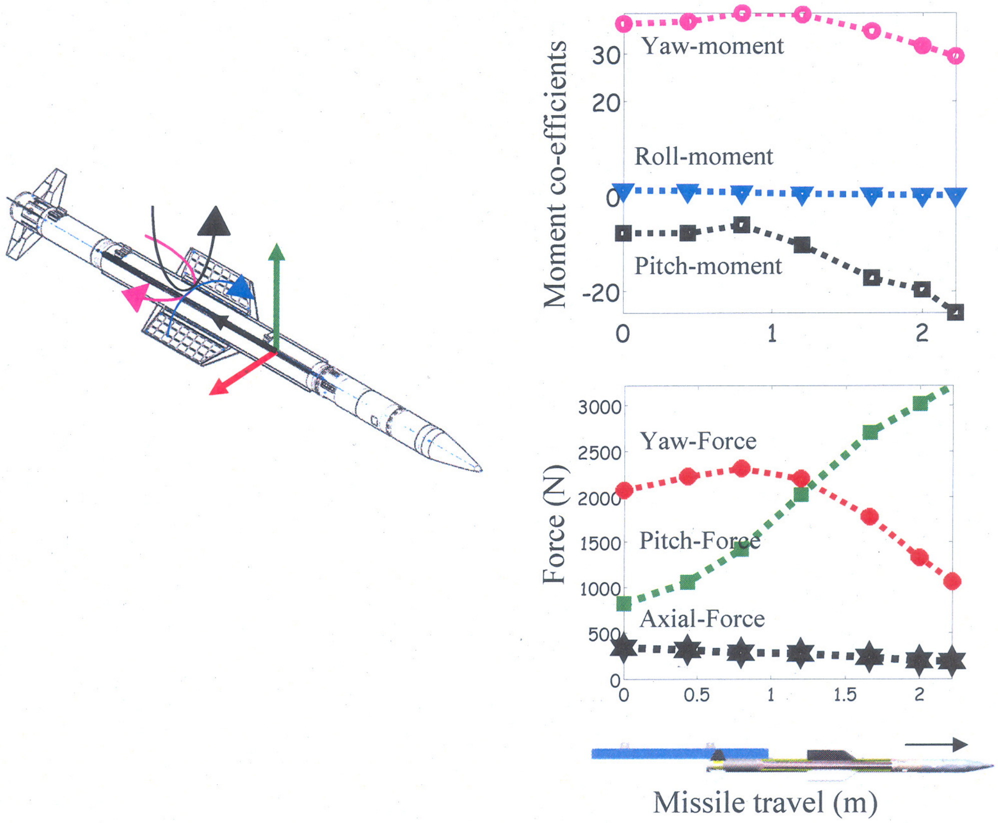


Fig.12 Variation of Aircraft Flow Field as a Function of Missile Travel on Rail

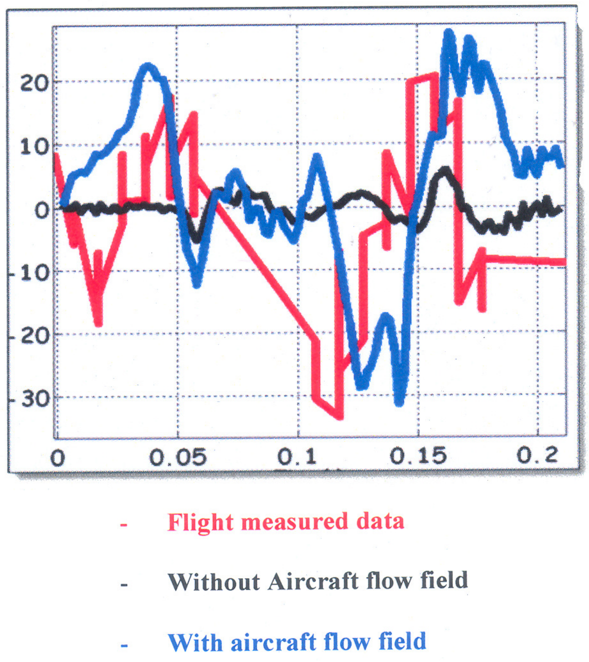


Fig.13 Variation of Roll Angular Rate with and without Aircraft Flow Field