INVITED PAPER

UAV DESIGN AND CONFIGURATION AERODYNAMICS - AN ADE EXPERIENCE

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Abstract

UAVs are becoming an essential part of the modern defense forces world over in the recent years. They are widely used for surveillance, reconnaissance, target for missiles and combat. They are available in various weight classes from few kilograms to tons. Apart from design of aircraft, establishing an accurate aero data base for control law design for the aircraft is a main challenge in itself. Aeronautical Development Establishment (ADE) is involved in the design and development of many UAVs for the last 30 plus years and has experienced several challenging design and engineering problems. Over the years, various UAVs like Ulka, Sparrow, Lakshya, and Nishant for different mission requirements have been designed and developed. The evolution of design methodology in ADE and the present configuration design activities of UAVs and aircraft stores separation studies with a focus on CFD are discussed in this paper.

Introduction

Aeronautical Development Establishment (ADE) is one of the leading organizations engaged in air vehicle design in the country. For any efficient aircraft design activity, several disciplines of engineering and technology have to synergistically combine their efforts to evolve a final design of an aircraft which is then flight tested several times to fine tune the design. The final proven design would evolve into a serial production of aircraft. The aerodynamic design of UAV configurations is more challenging as they have complex requirement of various payloads integration with the aircraft configuration apart from the regular shape and layout optimization. ADE has over thirty years of experience in UAV design. The configuration aerodynamics is one of the core competencies of Aerodynamic Division of ADE. The present paper focuses on the current UAV design activities of Rustom-II, a MALE UAV and aerodynamic analysis of other configurations

UAV Design Philosophy

The typical aircraft life-cycle phases are Research, Development, Testing and Engineering Phases (RDTE), Acquisition Phase, Operation Phase and Retirement Phase (Fig.1). The initial activity, whose associated cost is substantially lesser than the other phases, actually determines the success or failure of the project and determines the other activities.

Aircraft design is a very complex and iterative process. The design of a new aircraft is carried out with plenty of justified assumptions with verification and validation of the analysis carried out at various stages of design. The fidelity level of the aerodynamic model increases with the time from concept to flight. To carry out the UAV design effectively, ADE has adopted a spiral model in which the design effort spirals in towards the best possible design. The configuration that is being designed will be refined with the feedback from various aerodynamic experts with reviews before the first flight test. The ideal aircraft design spiral model is shown in Fig.2. The general phases of aircraft design are:

- Conceptual design
- Preliminary design
- Detailed design and Testing

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- Flight test

At ADE, the configuration and UAV system design are reviewed and refined through Peer Review, Preliminary Design Review (PDR), Critical Design Review (CDR) and Flight Readiness Review (FRR) before first flight.

The design of Lakshya and Nishant have been carried out extensively using engineering methods, wind tunnel testing and then finally with flight tests. In recent years CFD has matured as a better tool for aerodynamic analysis to provide valuable inputs to UAV design.

Rustom-II

The aircraft design is always dictated by the mission requirements. The main mission of reconnaissance and surveillance MALE UAV is to have wider coverage area for maximum time. This leads to high altitude and endurance requirements. Typical design requirements that have been considered for Rustom-II configuration are given in Table-1.

The major design drivers of Rustom-II are given in Table-2. Apart for normal aerodynamic shapes, the operational mission of UAV calls for carrying various external payloads which do not have proper aerodynamic shapes. Hence the payload drag has been obtained from wind tunnel testing. The design of Rustom-II has been carried out with weight estimation, airfoil design, wing and empennage sizing. Based on the preliminary studies, the AUW of aircraft is estimated to be 1800 kg. Based on the performance requirements, Rotax-914 engine is chosen to propel the aircraft. Several configuration options such as conventional tail/T-tail/V-tail, Tractor/Pusher type of power-plant, Conventional/Twin-boom type of configuration, Twin engine/Single engine, etc. were considered. The various concepts and configurations considered for the UAV during the conceptual design phase is shown in Fig.3.

Table-1 : Design Requirements for Rustom-II

Service Ceiling	32,000 ft
Max Operating Altitude	30,000 ft
Endurance	About 24 hrs
Cruise Speed	125-175 kmph
MaximumSpeed	Not less than 225 kmph
Stall Speed	Not more than 110 kmph
Max. TO Altitude	11,000 ft

Table-2 : Rustom-II Design Drivers

Design Driver	Parameter
Endurance	Fuel Capacity, Engine, High AR Wing
Service Ceiling	Engine Power, Propeller Efficiency, Drag, Aircraft Weight
Maximum Speed	Engine Power, Drag
Stall Speed	Wing Loading, C_{Lmax}
Take-off Altitude	Engine Power, C_{Lmax}
Take-off Distance	Engine Power, C_{Lmax}
Landing Distance	C_{Lmax}

Wing Sizing and Airfoil Design

After carrying out optimization studies with consideration for endurance, takeoff distance and weight, the planform of Rustom-II is designed with appropriate wing loading. A new high lift airfoil ADE-LS-E2 with high endurance parameter ($C_L^{3/2}/C_D$) has been designed with GAW airfoil as a seed airfoil using MSES, an airfoil design tool. The various airfoils designed for the UAV are shown in Fig.4. The aerodynamic characteristics of newly designed airfoil ADE-LS-E2 is verified (Fig.5) with wind tunnel tests and proven for its better performance (Fig.6).

Aerodynamic Analysis of RUSTOM-II

The aerodynamic analysis of Rustom-II has been carried out with various engineering methods, CFD and wind tunnel tests. Initially various layouts like tractor and pusher configurations with Conventional Tail, T-Tail and V-Tail configurations were considered for the UAV. After wind tunnel tests in IISc Open Circuit Wind Tunnel (Fig.7a), the tractor configuration with T-Tail was chosen based on the better aerodynamic characteristics.

The aerodynamic characteristics of the payloads are also established both by CFD and wind tunnel testing at IISc OCWT wind tunnel (Fig.7b). With the data obtained from the various wind tunnel tests and CFD analysis, the design is progressing with first flight scheduled in the near future. The air vehicle configuration of Rustom-II under development is shown in Fig.8.

Rustom-I

Rustom-I is a Technology Demonstrator UAV that was converted to UAV from a manned aircraft configuration. Generally UAV requires well designed airframe and systems like avionics, control system and telemetry. As a concurrent engineering concept (Fig.9), a well proven airframe was used to test the aircraft avionics and control system. The proven aircraft systems can be used for the new airframe that is being designed. The details of the changes made to LCRA are provided in Table-3.

Table-3 : Major Changes Between LCRA A/C and Rustom-I UAV

Parameter	LCRA	Rustom-I
Engine	Lycoming o-235	Lycoming o-320
BHP	116 HP	160 HP
Propeller	Bruce tiff	Sencinich
Prop Dia	1.57 m	1.73 m
A/C Weight	650 kg	780 kg
Fuel Capacity	200 liter	320 liter
Canopy	Bulbous	Faired flat
GPA	No	Yes
Antennae	No	Yes

Several changes were made to the original aircraft Light Canard Research Aircraft (LCRA) viz. installation of more powerful engine to increase climb performance, increase of fuel capacity to enhance endurance and removal of canopy for drag reduction. CFD analyses (Fig.10) were carried out to study the various issues such as:

- Effect of mounting antenna on R-I canopy.
- Effect of fuselage modification on the aerodynamic characteristics of R-I.
- Effect of mounting EO Payload on drag and intake mass flow.
- Air brake requirements.
- Air data sensor calibration to estimate the K_{ha} of the static port.
- Study of Air intake mass flow

Mini UAV Imperial Eagle

The hand launched man portable Mini UAVs are useful for obtaining short range intelligence with short turn-around time for carrying out the operation. They are very useful for Low Intensity Conflict and Battle Field Surveillance for on-field soldiers. The initial design requirements for man portable mini UAV are shown in Table-4.

Table-4 : Design Requirements/Targets for Imperial Eagle

Parameter	Specification
Length	1.0 - 1.4 m
Wing Span	1.3 - 1.6 m
Speed	40 - 90 kmph
Ceiling	15,000 ft (4572 m)
Operating Altitude AGL	30 m to 300 m
Endurance	50 - 60 minutes
Propulsion	Electric motor
Launch	Hand Launched
Payload	EO/IR Camera

After a detailed study about the mission and system requirements, the AUW of Mini UAV is estimated to be about 2.3 kg. Unlike other UAVs, it does not have a specific altitude as operating altitude. The operating altitude varies from sea level to 14,000ft MSL. Thus stall speed has been chosen for wing sizing criteria. A well established catalogue low Reynolds Number airfoil E214 is chosen for wing due its better endurance parameter $C_L^{1.5}/C_D$ at the operating C_L (Figs.11 and 12). As the flight test of low cost RC model is cheaper than the wind tunnel testing here the configuration was flight tested even before wind tunnel testing. The design is refined with both flight tests and wind tunnel testing. The design philosophy followed for Mini UAV design is illustrated in Fig.13. The fuselage is sized and shaped to accommodate all the equipments effectively. The low conventional tail is chosen to avoid the tail being in the downwash of wing. The COTS motor AXI-2826/12 with 12 x 8 propeller is chosen to propel the UAV based on performance requirements. The finalised configuration is shown in Fig.14.

The aerodynamic analyses have been carried out with VLM and CFD. The UAV has been initially flight tested in RC mode successfully and subsequently flown in autonomous mode.

Role of CFD in Aerodynamic Analysis of UAV

Engineering tools offer a good first-cut estimate to design problems. Classical approach to arrive the base line configuration using empirical and analytical methods is being used during the conceptual design phase. Many engineering and analytical tools are used for design and analysis during this phase. With the advent of high-speed computers, CFD has risen into prominence as one of the major tools used in the design process. Gone are the days when CFD was used when the configuration was sufficiently frozen. Now, we have risen to a level where we are able to integrate CFD into the design process. The following case studies will be covered.

- Validation of CFD approach with existing configuration
- Study of Roll Effectiveness of LGB Sudarshan
- Stores Separation Studies
- Minor modification of UAV Configurations
- Study of ground effect

Validation of CFD Approach

The CFD methodology has been validated with the existing database of Lakshya and Nishant configurations which have provided good confidence in CFD methodology adopted in carrying out the aerodynamic analysis (Fig.15).

Study of Roll Effectiveness of LGB

CFD studies had been carried out on the LGB Sudarshan configuration in order to determine the reason for roll ineffectiveness of canard. For canard deflection cases for e.g., $\delta = -12°$ case, the canard wake and trailing vortices interact with the Sudarshan flow field to change the pressure distribution both along the body and on the tail fins. The downwash of the deflected canards produces differential pressure on the starboard and port side of the Sudarshan ($\phi = 0$) that in turn produces a induced side force. In addition, the canard trailing vortices interact with the fins until α is high enough so that the vortices miss the rear fins. The differential pressure on the rear fins due to canard vortices is primarily responsible for the adverse roll effects. Flow interaction effects are similar for $\phi = 22.5°$ and $\phi = 45°$ cases also. The mesh generated is shown in Fig.16 and the contours of the vortices from canards are shown in Fig.17.

Store Separation Studies

Estimation of separation trajectories of external stores is an important task in the aerodynamic design area having an objective to define operational release envelopes. To define the flight envelope a very large number of store trajectory simulations are required to study the effect of parameters like flight speed, angle of incidence, altitude, store carriage location, presence of neighboring stores etc. on the carriage and release of stores. The store trajectory estimation technique should not only provide accurate results with quick turnaround time, but also be robust in terms of complexity of configuration and range of flight conditions.

A Cartesian grid based Euler code-PARAS coupled with trajectory evaluation module (a 6-DOF time integration module) developed at ADA has been used to estimate the separation trajectory of an external store from Jaguar fighter aircraft (Fig.18). The computed store trajectory results are validated with flight tests and found to be in good agreement (Fig.19).

Incremental Effect of External Payloads

The UAV mission revolves around the successful functioning of external payloads. It is inevitable to carry external payload with non-aerodynamic shape. The incremental change in aerodynamic characteristics due to payloads can be effectively studied using CFD. The incremental drag and moments due to 3-in-1 antenna on Nishant was studied using CFD analysis (Fig.20).

Study of Ground Effects

Aerodynamic characteristics of the UAV in presence of ground were established by using CFD and engineering methods. The RANS solver was used for ground effect prediction and shown in Figs.21 and 22.

Conclusion

The experiences of design of various UAVs at ADE over the decades have helped in refining the methodology of UAV design. The well evolved procedures ensure that best possible configuration is arrived effectively. While the final aero data is still being generated with large number of wind tunnel testing, the major portion of aerodynamic analysis is being carried out using CFD which helps in reducing design cycle time and provide valuable input to designers.

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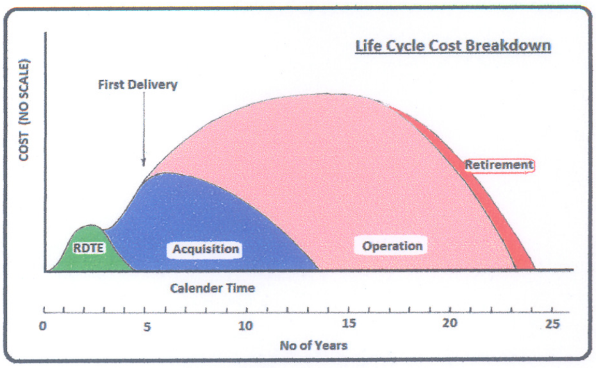


Fig.1 Aircraft Life-Cycle

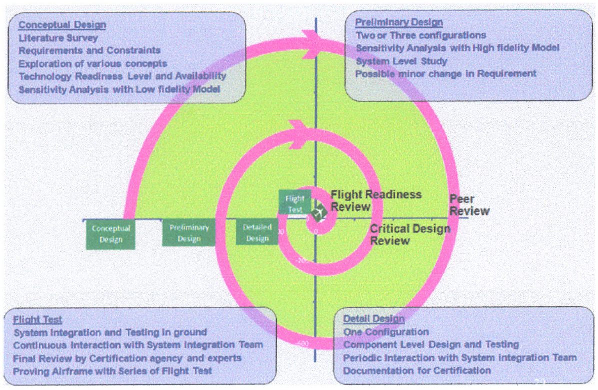


Fig.2 Aircraft Ideal Design Spiral

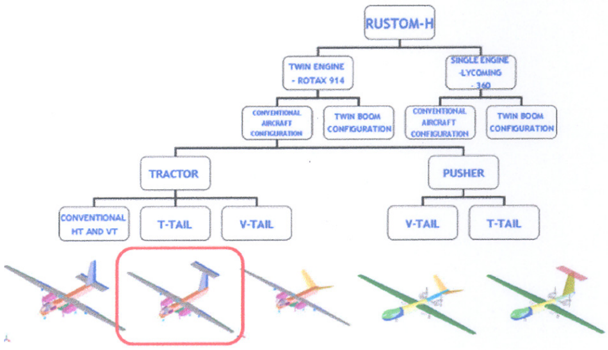


Fig.3 Various Configurations Considered for Male UAV

Fig.4 Various Airfoils Designed for Rustom-II

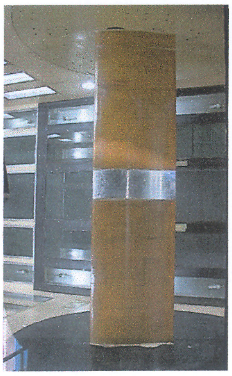


Fig.5 Wind Tunnel Testing of ADE-LS-E2 Airfoil

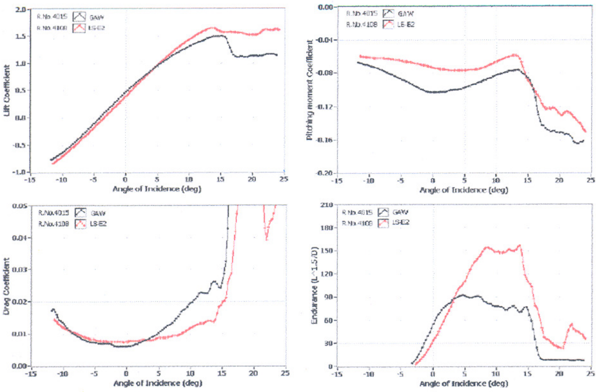


Fig.6 Design of ADE-LS-E2 Airfoil

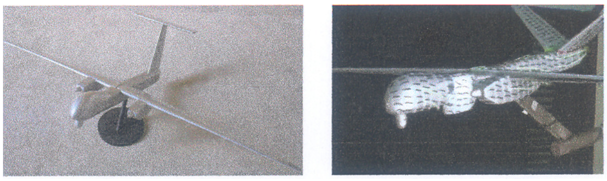


Fig.7a Wind Tunnel Testing of Rustom-II

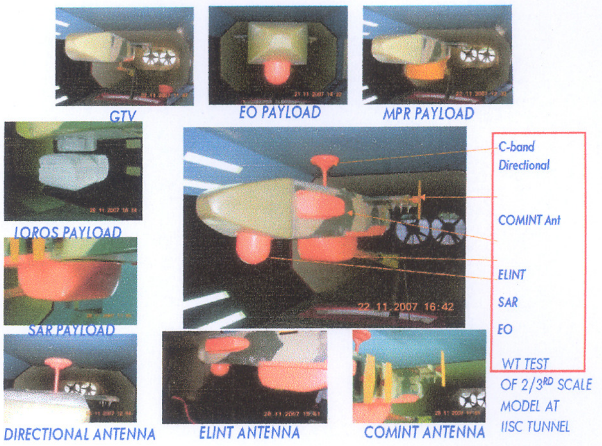


Fig.7b Wind Tunnel Testing of Various Payloads

Fig.8 Male UAV Rustom-II

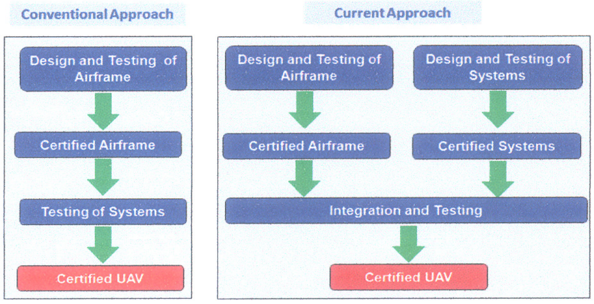


Fig.9 Concurrent Engineering Concept in Technology Demonstrator Rustom-I

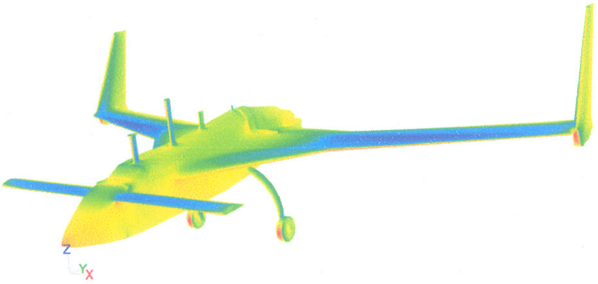


Fig.10 CFD Analysis of Various Antenna on Rustom-I

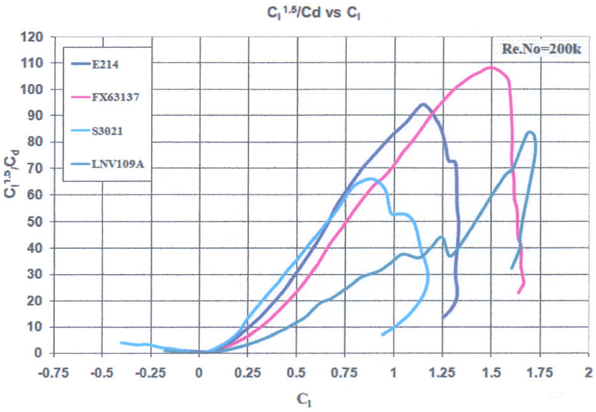


Fig.11 $C_l^{1.5}/C_d$ for Various Airfoils

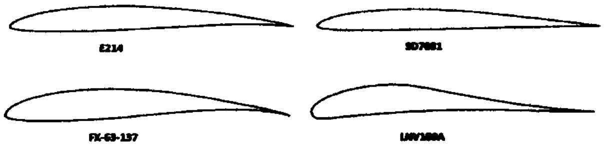


Fig.12 Various Airfoils Considered for Mini UAV

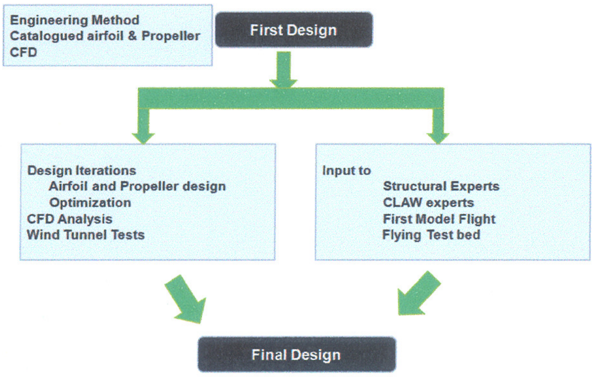


Fig.13 Design Philosophy Adopted for Mini UAV

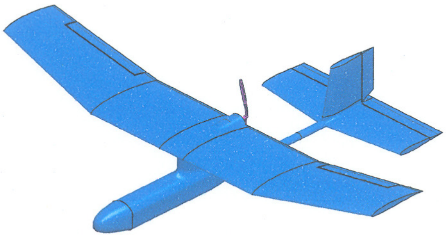


Fig.14 Conceptual Model of Mini UAV Imperial Eagle

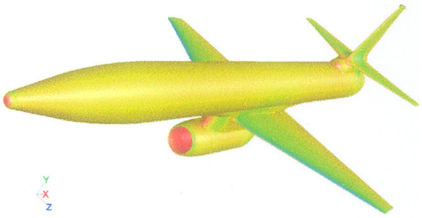


Fig.15 CFD Analysis of Lakshya

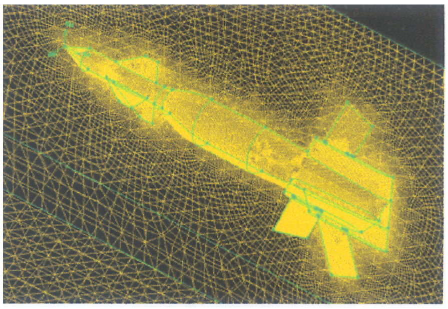


Fig.16 LGB-Sudarshan CFD Mesh

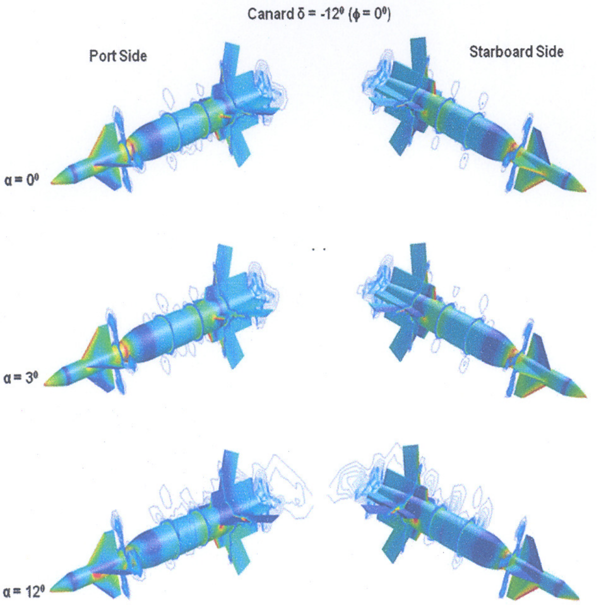


Fig.17 Sudarshan - Effect of Canard Vortices on Fins

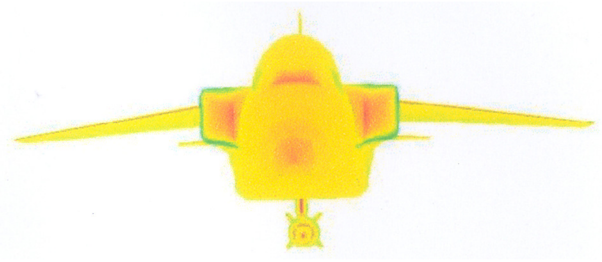
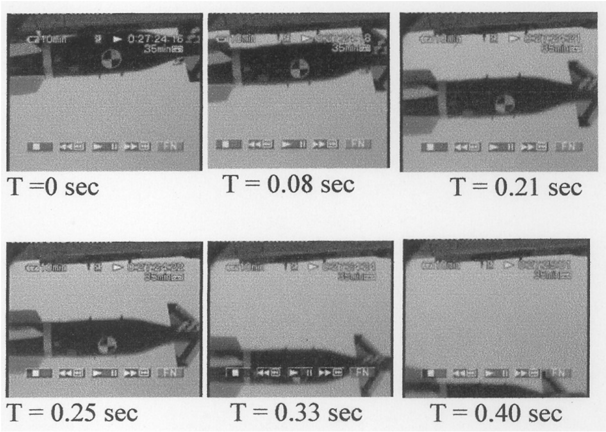


Fig.18 Pressure Distribution Over an A/C Store Configuration



T =0 sec T = 0.08 sec T = 0.21 sec

T = 0.25 sec T = 0.33 sec T = 0.40 sec

Fig.19 Release of Sudarshan from Jaguar Aircraft Using on Board High Speed Camera

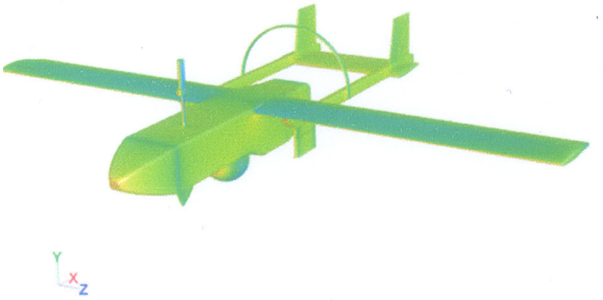


Fig.20 CFD Analysis of Nishant

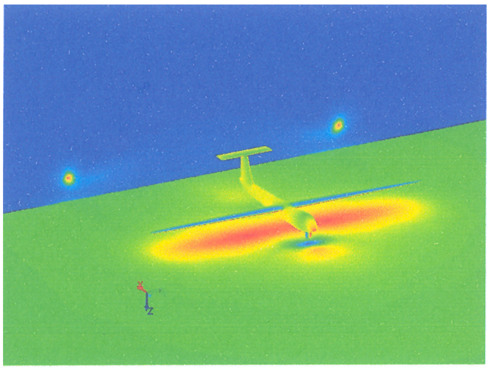


Fig.21 Pressure Distribution Over an Aircraft and Ground During Ground Run

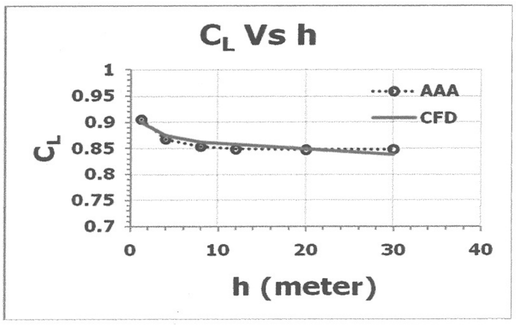


Fig.22 Effect of Height on C_L of Aircraft