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TOWARDS MULTI-DISCIPLINE CONCEPTUAL DESIGN METHODOLOGY FOR COMBAT AIRCRAFT

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Abstract

An assessment methodology has been developed for use during the conceptual/preliminary design phase to quantify the effectiveness of newly designed aircraft. The effectiveness is measured by a squadron Sortie Generation Rate (SGR). Key elements of this methodology were the establishment of link parameters between design synthesis and the main effectiveness disciplines. These were Reliability and Maintainability (R&M), Survivability / Vulnerability and Acquisition Cost. A programmable solid modeller was used to create a solid CAD assembly of the aircraft critical components. A ray tracing technique has been used to develop an interactive vulnerability assessment tool. A Mission Simulation Model (MSM) has been developed which typically simulates the operation of a squadron of aircraft and gives the operational activities such as flying sorties and maintenance actions. The methodology has been validated based on real data from recent conflicts. The application aspects of the methodology have been demonstrated by quantifying the effectiveness of two recent combat aircraft.

Introduction

An emerging trend in aircraft design synthesis is the integration of different disciplines in the design process. This approach allows a simultaneous, rather than sequential, analysis of the impact of these disciplines on the design evolution. A discipline integration in a design synthesis means that information output from any discipline is expeditiously available to all other disciplines as required. Recent studies have demonstrated this trend by integrating traditional design disciplines such as aerodynamic/structural of novel designs [1], aircraft stability/controlled composite wings [2], and aircraft performance/radar cross section (RCS) [3]. The intensive use of computer methods together with Computer Aided Design (CAD) techniques has provided an important

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steps toward shortening the design process and allowed fast and accurate, in-design-loop, calculations of basic design parameters such as mass, area, volume and center of gravity [4]

Design Disciplines of Combat Aircraft

A new aircraft progresses through three main phases of design before the start of production . In the first phase, conceptual design, the basic questions of configuration arrangement, size and weight, and performance are answered. The feasibility of the design to accomplish a given mission is established. The second phase, preliminary design, begins when the major changes are over. During this phase specialists in areas such as structures, landing gear, and control systems will design and analyze their portion of the aircraft. Finally, detail design contributes to the tasks necessary for production, such as production design and tooling/fabrication process set-up. It is during the conceptual phase that decisions are made to evaluate innovative integration schemes and feasible technologies that can lead to an effective aircraft design, which meets the requirements. In current fighter aircraft projects, mission effectiveness analysis has been a key factor in developing the most important design parameters. Although traditional trade-offs between design parameters such as lift, drag, propulsion and weight are still important, the design process has been expanded to include new disciplines that are more related to the operational environment of the aircraft. Recent conflicts have demonstrated that combat aircraft are the key to victory and places fighter aircraft at the top of a weapon system arsenal. a typical combat aircraft mission-scenario, as shown in Fig.1, an aircraft takes-off and flies as fast as possible to the target area, locates the assigned target, delivers its weapons on the target, and returns to its base.

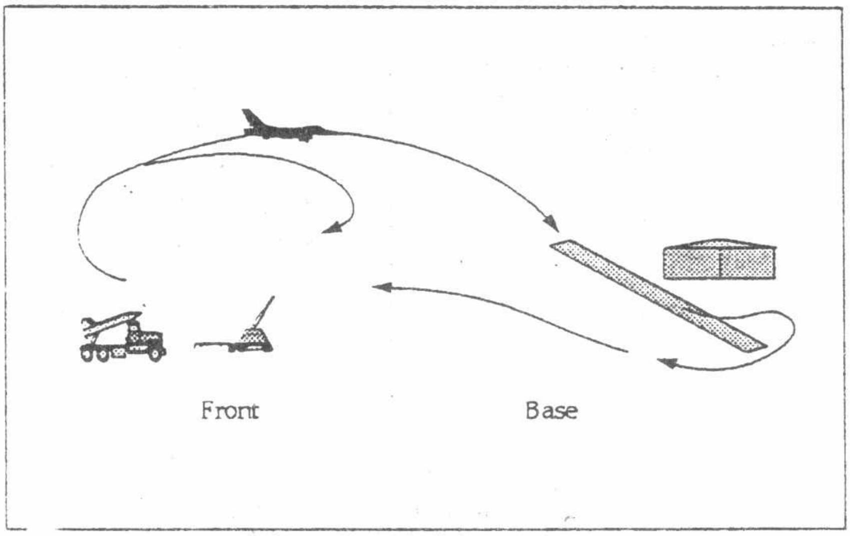

Fig. 1 Typical mission scenario

An analysis of this scenario reveals that the degree of success of this mission depends on:

1. The aircraft availability to conduct the mission.
2. The performance characteristics of the aircraft.

3. Target location and identification capability.
3. Effectiveness of the aircraft weapon's package.
4. The aircraft survivability characteristics.

The availability of the aircraft affects its effectiveness because the more aircraft are available, the higher the probability that the target is killed. Availability is affected by the aircraft Reliability and Maintainability (R&M) and logistics factors such as maintenance personnel, damage battle repair and spare parts availability. The effectiveness of the mission is always affected by aircraft survivability. Aircraft with more survivability will return from a mission more often, and hence more aircraft will be available for subsequent missions. Aircraft payload affects the mission effectiveness because the more payload carried the more targets are likely to be killed. Also the higher the payload the fewer sorties will be required to kill a target and hence the less probability of losing an aircraft. Aircraft performance capabilities affect effectiveness by allowing the aircraft to get in and out of the target area in a short time and allowing more effective tactical flying maneuvers as well as affecting survivability. Aircraft radar signature influences the probability that the aircraft will be detected during its mission. This feature greatly influences the effectiveness and could be traded with increasing the pay-load in favour of some performance characteristics. Fig. 2 shows some of the main effectiveness disciplines of a combat aircraft design. It could be seen that the effectiveness factors are different and inter-elated.

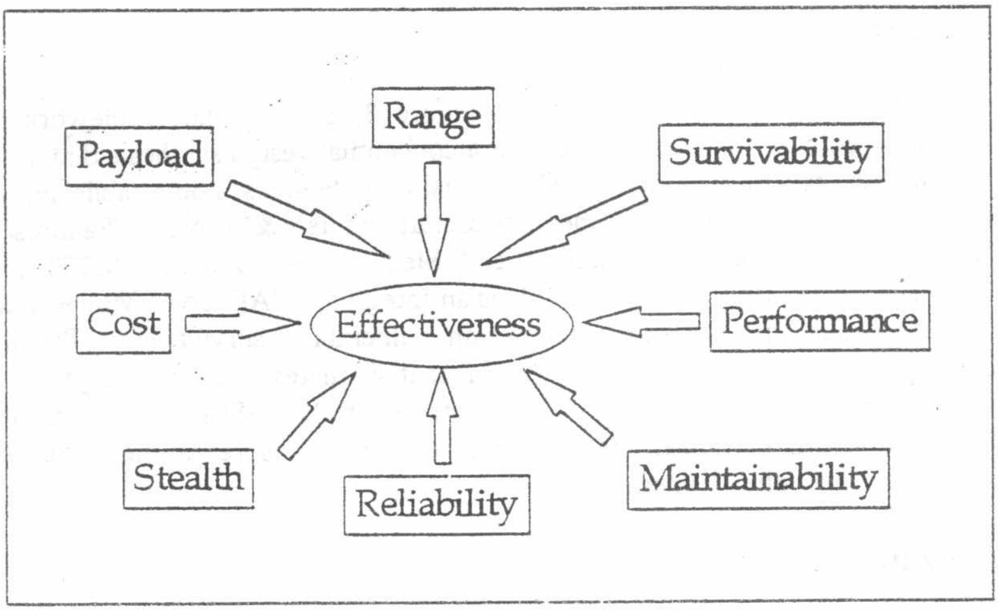

Fig. 2 Combat aircraft effectiveness disciplines

SGR, Design Disciplines Link

Combat aircraft Effectiveness is a wide-term and difficult to quantify by a single measure. The following measures are the most widely used by Air Force analysts to evaluate the effectiveness of a fighter aircraft:-

Percent bombs in target area.
Cost per target kill (Bangs per Buck).
Payload per sortie.
Payload-range.
Kill ratio.
Sorties per day or Sortie Generation Rate (SGR)

The SGR was selected in this study to be the measure of aircraft effectiveness. The SGR reflects more of the design-related effectiveness disciplines than other measures because:-
If the aircraft speed (performance) is high it will get to the target area and back home in a shorter time, which means a higher SGR.
If the aircraft is reliable, it means that less failures are likely to occur, hence high availability and finally a higher SGR.
If the aircraft has good maintainability design features, the shorter the failure repair time will be and hence there will be more availability and finally a higher SGR.
If the aircraft is survivable there will be a lower probability of combat loss, hence a higher SGR.

Methodology Layout

A group of four modules, as illustrated in Figure 3, provide the framework of the proposed methodology. The first module is a conceptual design synthesis that serve as the driver for the rest of the modules. The second module focuses on establishing a link between the design characteristics of the new aircraft and its R&M (No. of Failures/1000 flying hours for the Reliability Discipline and Mean Time To repair MTTR for the Maintainability Discipline) The third module is an Integrated CAD Solid-Modeller which has been developed to assess the new design vulnerability/survivability. The fourth module is a Mission Simulation Model (MSM) that simulates an air campaign of, say, a squadron of the designed aircraft. The objectives of the MSM is to translate the parameter changes in the other modules into a single measure of merit for use in quantifying the design effectiveness.

Design Synthesis (CONCEPT)

The design synthesis CONCEPT starts by defining the aircraft requirements which include parameters such as the aircraft range and payload, takeoff and landing performance, maneuverability and speed requirements. Also, the general aircraft arrangement, such as number of engines and tail layout, are defined. The takeoff weight is then calculated using the statistical iterative method described by References [5,6]. The major aircraft items are then sized based on the design algorithms of Reference [7]. Modifications have been developed and added to the design synthesis based on the requirement that critical aircraft components must be defined for the vulnerability/survivability module. Such items are the landing-gear and control surfaces. Figure 4 gives the design synthesis flowchart.

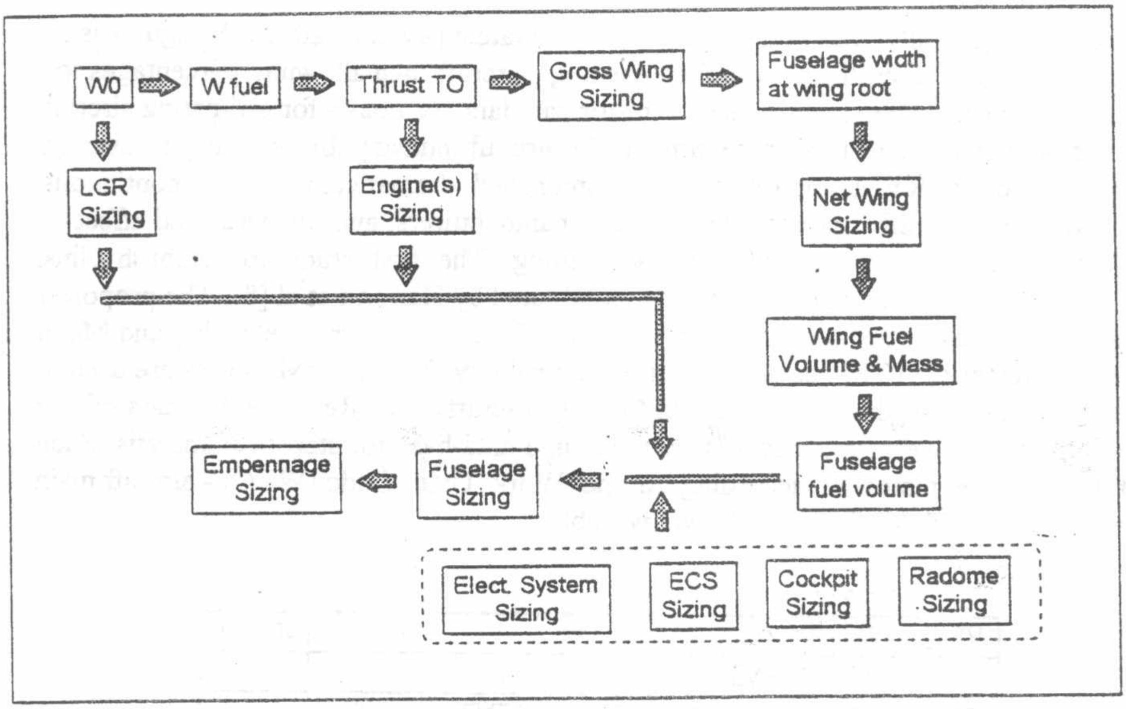

Figure 3 Methodology layout

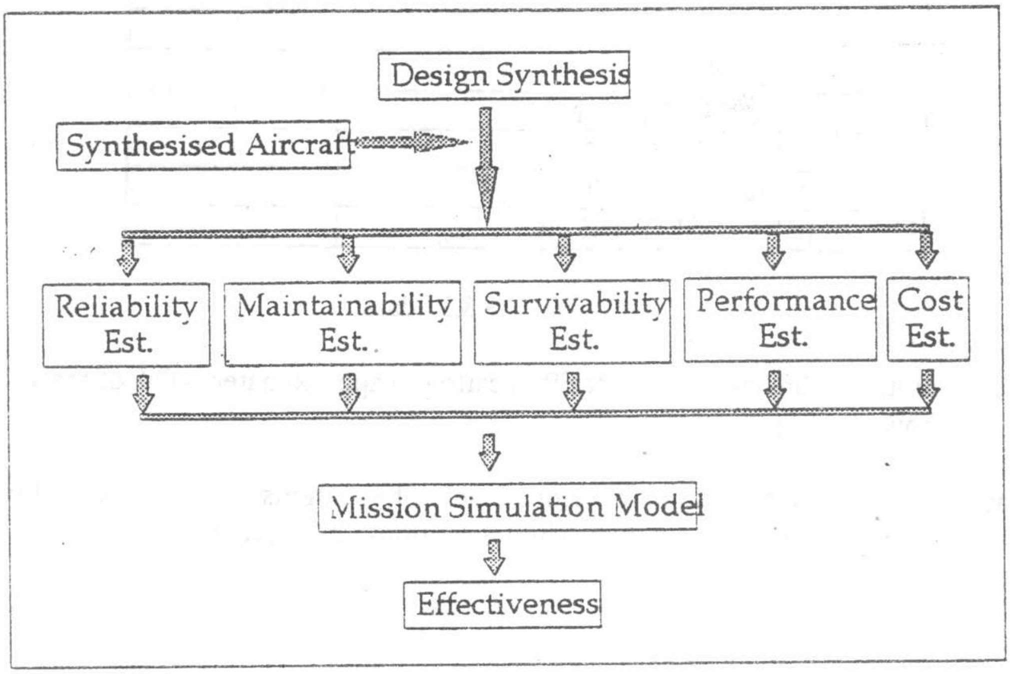

Figure 4 CONCEPT flow chart

R&M Estimation

Aircraft R&M is becoming a growing importance as a dominant factor of the cost effectiveness of any aerospace vehicle. R&M contributes to more than 70% of the cost-related driving factors which are defined at the conceptual/preliminary design phase of an aircraft. The generally-accepted procedure to estimate a new aircraft R&M figures is to compare the new aircraft to a similar existing aircraft then allowing percentages for technology improvements. The use of historical data as a basis for estimating aircraft R&M is a widely accepted procedure in the aircraft industry. In the transport aircraft industry, aircraft R&M prediction was improved dramatically by the continuous feedback from aircraft operators and aircraft manufacturers, and the perceived effect of R&M on airlines' revenues and flight scheduling. The first study to establish a link between R&M and aircraft design was conducted by Harmon et al [8]. The proposed methodology uses the aircraft Failure Rate (FR) for the aircraft reliability and Mean Time to Repair (MTTR) for the aircraft maintainability. These R&M figures are used in order to investigate the impact of R&M on the aircraft SGR. Recent R&M data of five current fighters were collected and compiled in a data-base for statistical analysis. Each aircraft data are tabulated according to the Work Unit Code (WUC) - aircraft main systems - of the US Air Force as shown by Table 1.

WUC	SYSTEM	FR	MTTR
11	AIRFRAME		
12	FUSELAGE COMPARTMENT		
13	LANDING GEAR SYS.		
14	FLIGHT CONTROLS		
...	....		
...	....		
...	....		
77	PHOTO/RECONN		
91	EMERG. EQUIP		
96	PERSONNEL EQUIP		
97	EXPLOSIVE DEVIC		

Table 1 WUC R&M data

It was found that 80% of the aircraft FR is caused b approximately 40% of the aircraft systems as shown by Figure 5.

Correlation analysis was used to develop a set of equations that relates R&M to the aircraft design/performance parameters. These equations are found in Ref. 9.

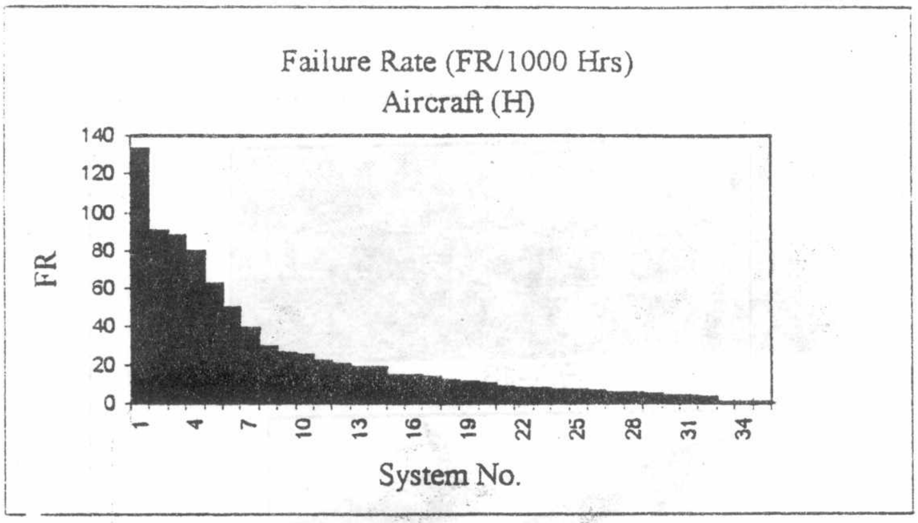

Fig. 5 Sample of compiled FR.

Survivability, Susceptibility and Vulnerability

Aircraft combat survivability is defined as ***"the capability of an aircraft to avoid and/or withstand a man-made hostile environment"*** [10]. The inability of an aircraft to avoid a threat is referred to as the ***Susceptibility*** of the aircraft. An aircraft's susceptibility can be measured by the probability that the aircraft is hit while on its ission, (P_H). The inability of an aircraft to withstand any hits by the hostile environment is referred to as the ***Vulnerability*** of the aircraft. An aircraft's vulnerability can be measured by the conditional probability the aircraft is killed given a hit, ($P_{K/H}$). The survivability of an aircraft can be measured by the probability of survival, (P_S), which depends on the aircraft's susceptibility and vulnerability according to the equation:

$$P_S = P_H \; P_{K/H}$$

The importance of vulnerability in the design of military aircraft increased dramatically in the middle 1960's when many aircraft, not specially designed to be survivable, were shot down in Southeast Asia conflict. 5,000 U.S. aircraft have been lost in the years from 1963-1973. Since then, vulnerability , and survivability in general, has emerged as a distinct and important design discipline. Most of the recent combat aircraft incorporate some vulnerability reduction features. The F/A-18, . Fig. 6, was the U.S. Navy's first aircraft in which vulnerability reduction requirements has influenced its conceptual design. Such reduction features include adequately spaced, twin-engine arrangement, twin canted fins and two independent and separated hydraulic subsystems. The A10 (Tank Buster) is another example of an aircraft of which vulnerability discipline has been implemented at the conceptual phase.

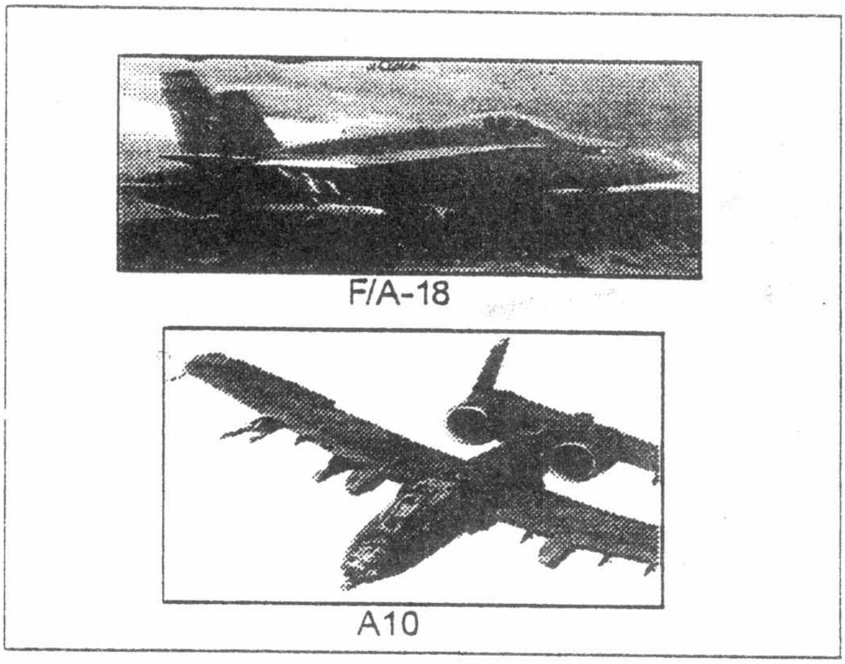

Fig. 6 Vulnerability features of the F/A-18 and the A10

Aircraft vulnerability is influenced by the location and orientation of critical components inside the aircraft as well as the size and redundancy degree of these components. Solid modeling CAD techniques are used to model the aircraft critical systems as defined by the CONCEPT module. A programmable solid modeller was used to create a solid CAD representation of the designed aircraft and its inside systems/components. The aircraft nose is selected to be the reference point since it is the station (X=0) in any aircraft design synthesis. The reference vector is chosen to be the line passing through the reference point and the center of the aircraft engine face, Fig. 7.

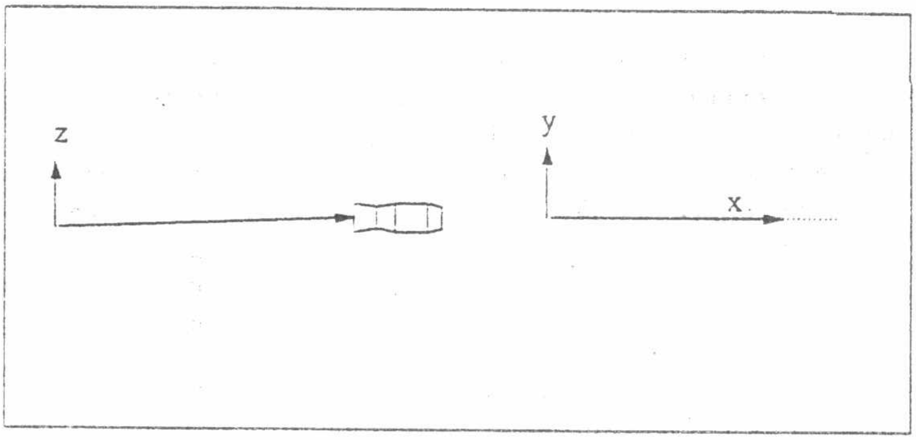

Fig. 7 Reference point and reference vector

The location and orientation of the aircraft components/sub-components are set relative to the reference point and reference vector. Also for each main component there is a reference point which works as an insertion point which works as an address in the assembly process. PARASOLID [11] solid modeling routines are used to create the aircraft components either by Basic Solid Primitives (i.e. sphere, box, cone etc.) or by conducting Boolean Operations to get the right solid shape. Fig. Shows a wire-frame and a solid rep. of an engine.

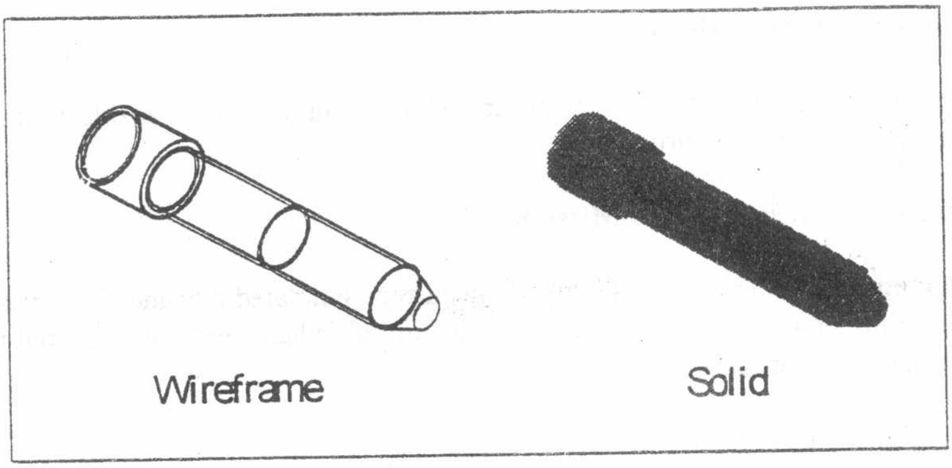

Fig. 8 Engine wireframe and solid model

Lofting routines have been developed to model shapes that could not be approximated by BSP or Boolean operations, such as the fuselage and the engine ducts. Ray tracing techniques are used to develop an interactive shotline and vulnerability assessment of the designed aircraft. Each ray represent a fragment of the analyzed threat type such as Anti Aircraft Artillery (AAA) or High Explosive warheads. A list of components that has been penetrated by the shotlines (rays) is created to perform the Kill Tree Analysis as given by the MIL-STD [12].

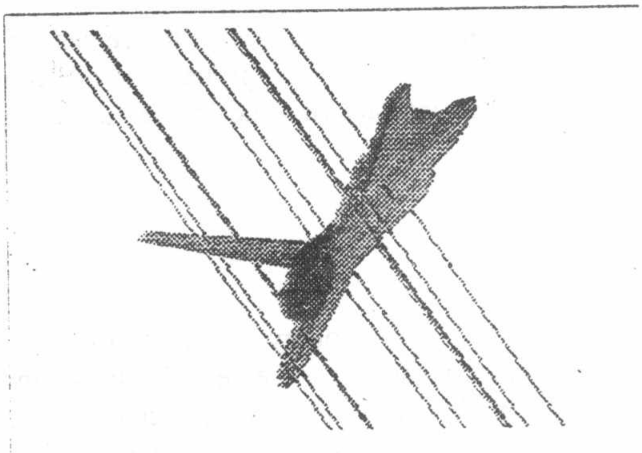

Fig. 9 Solid model of an aircraft & shotlines

Mission Simulation Model

The MSM is a discrete event simulation program that translates the aircraft performance, R&M and survivability into a measure of interest to the designer, the sortie generation rate (SGR). The MSM simulates the operational tasks of a squadron of a defined number of aircraft, such as scheduled and unscheduled maintenance. The simulated operational day starts by calculating random launching times of a defined number of sorties per day.

The simulation time increment is in minutes that are translated to a 24 hours/day time scale. For each minute the following discrete events take place:-

1. Send Aircraft to a Mission

When the current simulated time is equal to a sortie call time, an available aircraft is launched and assigned for the sortie.

2. Return an Aircraft From a Mission

Aircraft are returned from a mission when the current simulated day and time equal to the day and time of a launched aircraft. When an aircraft is launched, the expected time and day of return is computed.

3. Send Aircraft to Maintenance

When failure occur, based on the estimated system failure rate and flight hours accumulated for each system, returning aircraft with failure(s) are sent to maintenance.

4. Return an Aircraft From Maintenance

This event takes place when the current simulated time and day is equal to the time and day that has been estimated to repair the aircraft.

5. Withdraw Aircraft From Inventory

The attrition rate (kills/1000 sorties) is a probabilistic figure derived from the aircraft survivability (P_S) . The vulnerability figures (probability of kill given a hit) are automatically estimated from the interactive solid model of the attacked/designed aircraft.

Illustrative Example

To illustrate the capabilities of the methodology, a comparison of the impact of the number of engines on aircraft effectiveness is presented. The long-running debate about single-engine versus twin engine fighter aircraft is still alive. Doubling the number of engine and, consequently, increasing the volume and surface of the powerplant, adds, through to a smaller degree, to the likelihood of an aircraft being hit by a gun or a missile weapon system. Both configurations (single & twin) are vulnerable particularly to the same degree, e.g., when hit by guided missile with IR homing head; however, it is not necessary so that an engine being hit would cause damage or failure of the other. Historically, the combat survivability of a twin-engine aircraft is on the whole higher, by some estimates of 15 to 25% higher [13]. Based on similar operational requirements, two aircraft (single and twin) are designed using the current methodology. Figure 9 shows the results of 20 hit trails which are fired towards both aircraft. These values are averaged to give a P_{KH} of 0.2 for a single engine and 0.152 for the twin configuration. The twin-engine configuration is 24% more survivable (less vulnerable) than that of a single-engine. This agrees well with the historical estimates reported in Ref. [13].

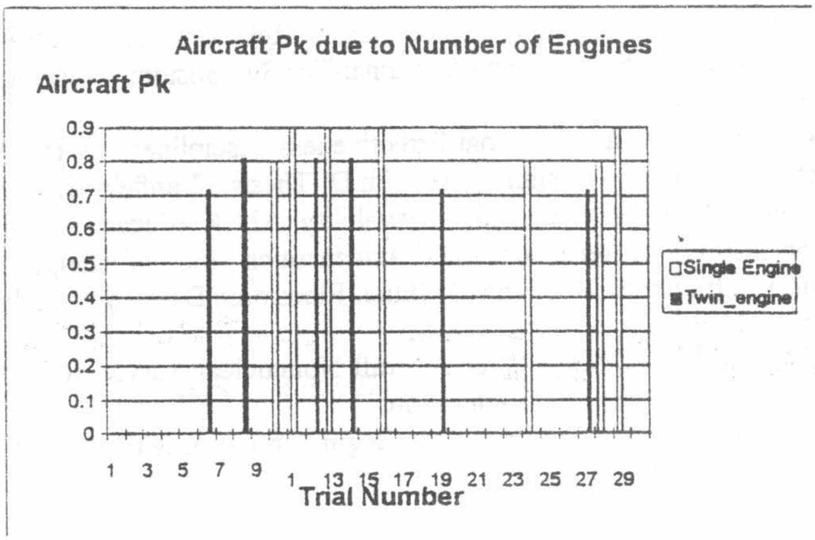

Fig. 10 P_K values for 20 random shots

Concluding Remarks

The effectiveness methodology can provide the designer with insights into the impact of different disciplines on combat effectiveness. The automatic solid modelling of a designed aircraft and linking the vulnerability and R&M figures to the aircraft design variables enables examination of design tradeoffs and optimization processes with these new disciplines. Combat effectiveness in terms of SGR and total weight of weapons on target over a given period of time provides a single measure of merit for comparing design options.

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