Sādhanā, Vol. 12, Part 3, March 1988, pp. 219–228. © Printed in India.

Integrated design approach for advanced aerospace vehicles

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Abstract. Advanced aerospace vehicle design requires special design features that should meet the mission requirements of high payload to weight ratio in the case of space launchers and low radar cross-section for specific missiles/aircraft. The conventional design packages used are discussed in relation to their constraints. An interactive integrated design approach to eliminate the constraints imposed by individual design modules through interface design modules is discussed. Typical examples of such interface design modules are given. Also, a computer network necessary for an interactive integrated design approach interfacing the mainframe with a computer-aided design and drafting system and parallel processing is presented.

Keywords. Integrated design approach; advanced aerospace vehicles; interface design module.

1. Aerospace vehicle system design

Recently, a review revealed that the design effort used for a launch vehicle system is about 300 man-years and for a missile system about 200 man-years. If the design has to be completed in two years' time, at least a 100 designers of various disciplines will have to be provided, and again for design of other similar aerospace systems, a number of designers have to be deployed. As can be seen from figure 1, for a launch vehicle system or missile or aircraft, technical specifications are generated by a team of specialists to meet the mission requirements. This leads to subsystem characteristics with different alternatives. After a detailed review and based on the experience gained, the subsystem options considered are evaluated in the kinematic system model for the performance. Estimation of reliability and cost would also be carried out. This will lead to total system specifications with subsystem configurations. Subsequently, detailed design of subsystems is carried out for aerodynamic configuration, airframe, guidance, control and propulsion. The design packages for these subsystems and previously generated data banks are utilized in arriving at detailed designs.

Once the subsystem hardware is realized and tested, critical design reviews are carried out with available test data. Guidance and control hardware and software

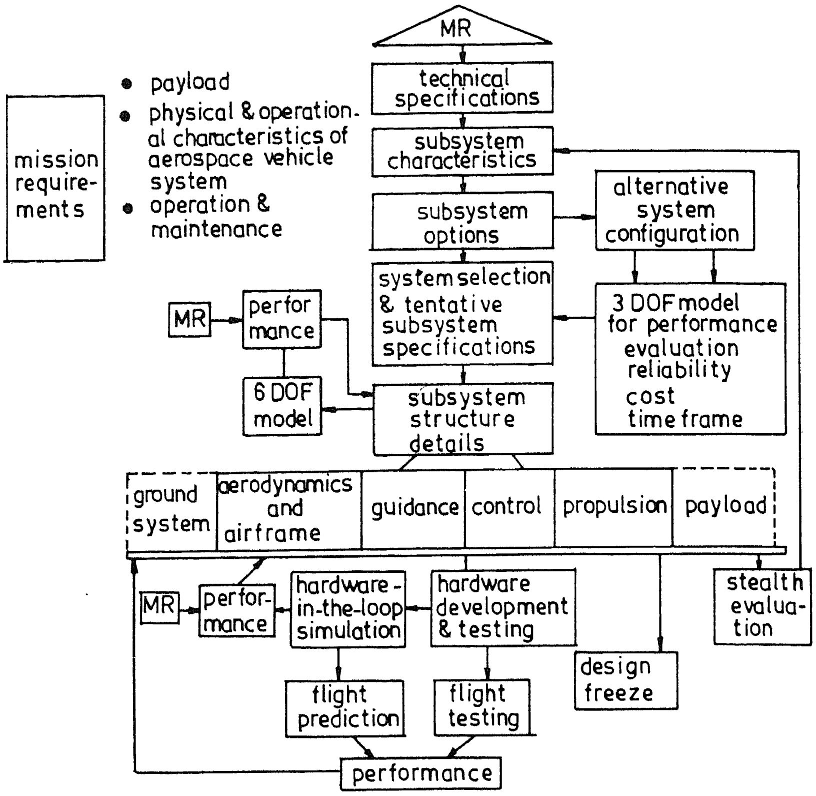

Figure 1. Aerospace vehicle system design – an outline.

like the inertial navigation system, on-board processor and autopilot go through hardware-in-loop simulation (HILS) for detailed performance evaluation. Various subsystems are integrated and checked out through the flight test. The flight test data are again fed back to the designers after post-flight analysis to further improve the designs. This completes the design cycle for which, based on missile and launch vehicle experience, about 200 to 300 man-years are required. How the various subsystem level design packages can be linked and integrated into a total system design package for the aerospace vehicle is the focus of our attention. The number of design man-years used has been high since the design of the subsystems is done through sequential rather than parallel operations. A 6-DOF* trajectory run for evaluation of a typical system having subsystem modules numbering about 200 takes about an hour of computer time on a third generation computer system. To reach a final design with failure module analysis incorporated, it may be essential to have 2000 simulated computer runs. Also each design package, e.g. aerodynamic design, starts with certain constraints followed by the subsequent design, like structural design. Hence these constraints are not seen together in a sequential design process. It is essential that these system constraints are seen in totality so that unrealistic constraints can be removed during the integrated design process.

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[*] DOF – degrees of freedom.

2. Interface design modules

Based on the design efforts carried out, the three typical design packages or modules given below are considered for interfacing conventional design modules:
i) aero-propulsion interaction for a ramjet;
ii) structure-control interaction of a typical aerospace vehicle;
iii) integrated electrical-structural design.
These examples focus on the subsystem level interactions to be taken care of in the integrated design approach.

2.1. *Aero-propulsion interaction for a ramjet*

The integrated design of an aero-propulsion system like a ramjet needs multi-design packages such as vehicle body flow field analysis, air-intake internal flow field analysis, analysis of interaction of multiple intakes, combustor flow field analysis and matching of combustor and intake operations.

For high performance axisymmetric intake of the ram rocket system operating upto a Mach number of 3 and angle of attack upto 5°, the typical critical pressure recovery for the intake alone will be of the order of 0·82 at starting, as shown in figure 2a. However, as can be seen from figure 2b, when the fuselage is integrated with the air intakes, the critical pressure recovery for the same Mach number and angle of attack reduces to 0·65 for a cruciform configuration of 4 air-intakes positioned at 45° from the vertical. Figure 2c gives the variation of fuel flow rate with time for matching of the intake to the combustor. In such a system, where the propulsion performance is matched with aerodynamic pressure recovery, the specific impulse obtained from figure 2d for the integrated ram rocket system with a pressure recovery of 0·6 is about 580 s. The specific impulse is therefore twice that of the conventional rocket propulsion system. The above example suggests how the propulsion, aerodynamic and combustion phenomena are all interlinked, and hence, the need for the designer to have an insight into the mechanism of the three subsystems.

2.2 *Structure-control interaction of typical aerospace vehicle*

Many of the guided and controlled aerospace vehicles have to be designed for flexibility of the airframe due to flight loads, engine deflections etc. In the case of aerospace vehicles, even though the vehicle is flexible, the control system designers normally use the rigid vehicle approximation to start with, and then by iterative process, consider the effect of vehicle flexibility on control system design after flexibility data of the airframe become available. The bending mode shape for a typical aerospace vehicle is given in figure 3a. For the control system designer, the first input is the type of structural frequency variation with respect to time of flight as shown in figure 3b. The possible design is normally based on 'moderate' joints at intersections. The structural frequency will be of the order of 30 Hz and this needs to be separated from the control frequency by a factor of at least 4 in order to make the compensator design possible. In figure 3c, the control system performance of a rigid vehicle, an uncompensated flexible vehicle and compensated flexible vehicle are shown. It is seen that if the vehicle is flexible, the control system gain margin is reduced. If the flexibility effects are not addressed during the design of the control

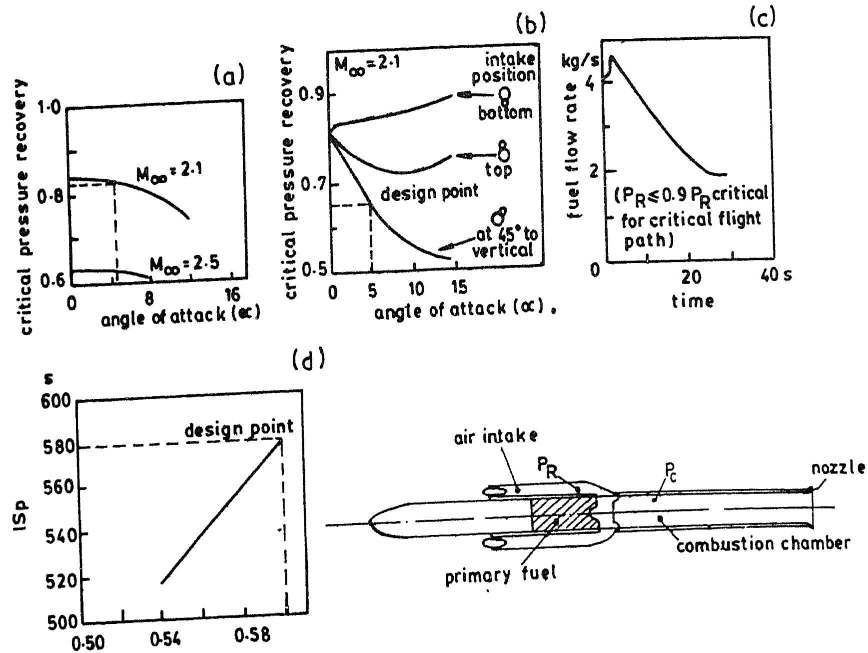

Figure 2. Aero-propulsion interaction for a ramjet. The interface packages required are (i) vehicle body flow field analysis; (ii) air-intake internal flow field analysis; (iii) analysis of interaction of multiple intakes; (iv) combustor flow field analysis; (v) matching of combustor and intake operation. (**a**) Stand-alone performance of axisymmetric intake. (**b**) Installed performance of axisymmetric intake. (**c**) Curve obtained by matching of intake to combustor. (**d**) Typical ISp vs. intake pressure recovery (intake operation super critical).

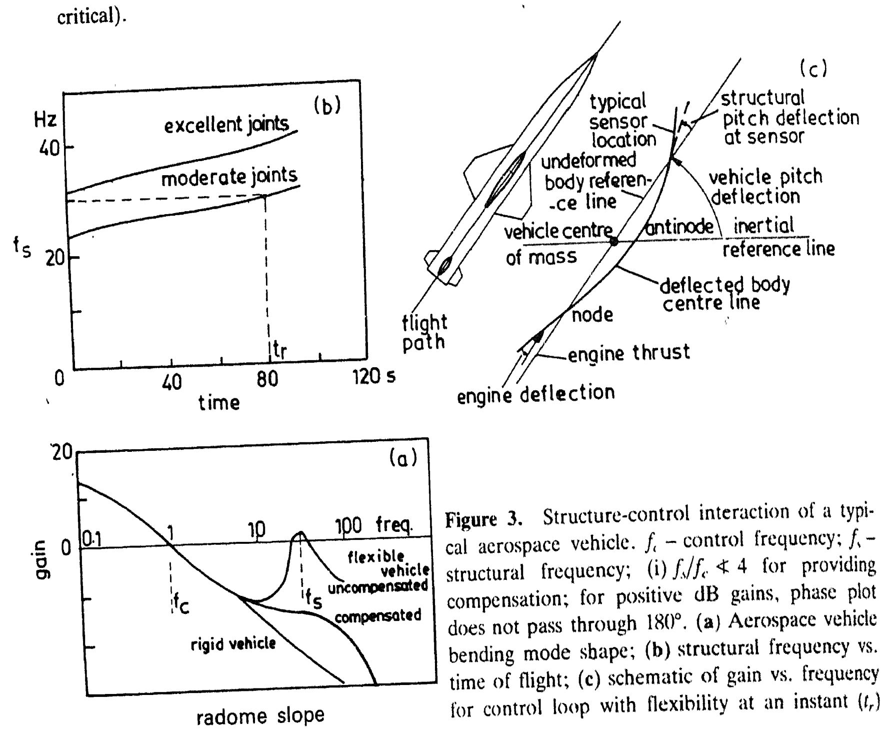

Figure 3. Structure-control interaction of a typical aerospace vehicle. f_c – control frequency; f_s – structural frequency; (i) $f_s/f_c \nless 4$ for providing compensation; for positive dB gains, phase plot does not pass through 180°. (**a**) Aerospace vehicle bending mode shape; (**b**) structural frequency vs. time of flight; (**c**) schematic of gain vs. frequency for control loop with flexibility at an instant (t_r).

system, the response of the control system in flight becomes oscillatory, leading to instability at certain flight conditions along the trajectory. Hence, it is essential to integrate the control system design package and the structural design so that a compensated control system is possible with sufficient gain margins.

2.3 Integrated electrical-structural design

The antenna system of the homing-seeker for a typical missile system is housed in a composite radome. While the radome has to meet the aerodynamic shape and structural requirements, the design of the radome structure is also driven by the acceptable near-field antenna pattern with minimum loss. In order to meet the above requirement, the thickness of the structure is obtained by taking into consideration the dielectric constant and loss tangent of the radome material. The shell thickness, established from the electrical considerations as shown in figure 4 is then analysed for buckling and bending behaviour. The typical shape of the radome is a tangent ogive with L/D ratio of 2·5 to 3 as shown in figure 5a. The designer has many choices for radome material from glass-polyester, glass-epoxy and glass-polyimide to ceramic for various Mach numbers and a temperature range of 100–600°C as shown in figure 5b. The designer can select the glass-epoxy radome or ceramic radome depending upon the loss tangent requirement for electrical design. As can be seen in figures 5c and d, for the glass epoxy, the loss tangent rapidly increases with temperature and the dielectric constant is also high, whereas for the ceramic radome, the rate of increase is much lower. Based on the mission requirement, weight and temperature constraints, a ceramic or a glass epoxy radome has to be selected as indicated in figure 6a. It can be seen from the radiation pattern of the antenna without the radome that the received power is about 20 dB and with the glass-epoxy radome it is about 21 dB. Another most important performance requirement is to minimize the side lobe of the radiation pattern. For a fused silica ceramic radome, the side lobe is lower compared to the glass-epoxy radome. The designers have to translate these factors into electro-mechanical design. This experience needs to be validated and built into the design package.

In the case of guidance, the guidance law has to be chosen suitably to keep the miss-distance to a minimum. For a typical surface-to-air missile, a 5 m miss-distance will result only from a radome slope of 0·07 as shown in figure 6b. For a

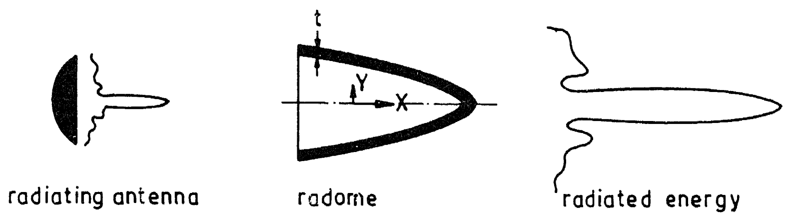

Figure 4. Integrated electrical-structural design. Field – $F_o(X, Y)$; near field – $F(X, Y)$; $T'(\theta)$ – transmission coefficient; Φ' – insertion phase.
$F(X, Y) = F_o(X, Y)|T'(\theta)| \exp(-J\Phi')$, where T' and Φ' are F_n of thickness t, dielectric constant ε, Loss tangent $\tan\delta$. The sequence of steps in the operation is (i) obtain t as F_n of X to get an acceptable near field pattern; (ii) check for buckling and bending strengths; (iii) finalise t.

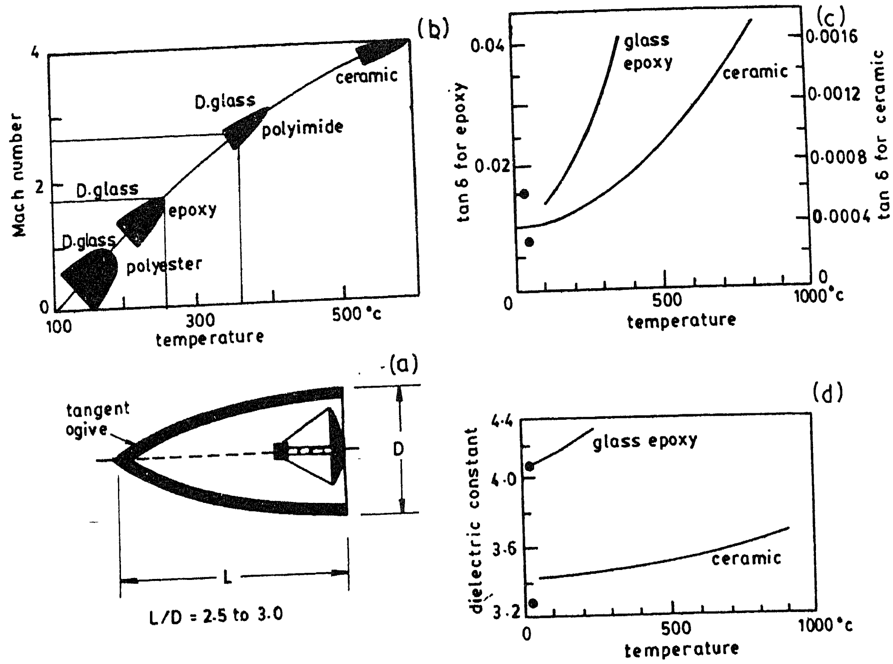

Figure 5. (a) Typical radome geometry; (b) choice of materials for the radome; (c) variation of Loss tangent with temperature; (d) variation of dielectric constant with temperature.

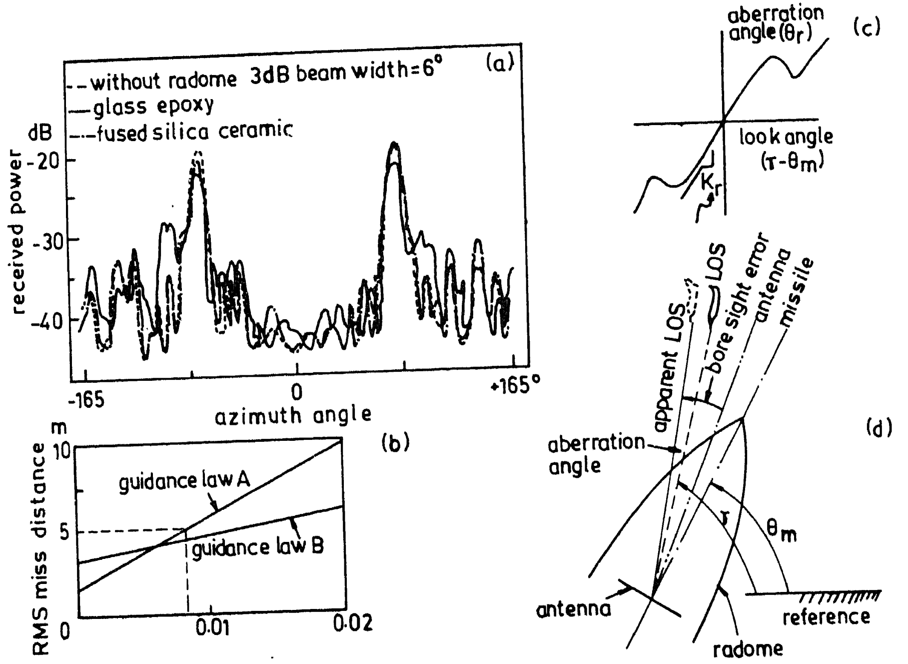

Figure 6. Radome guidance-performance. (a) Radiation patterns of the transmitting antenna with ceramic and epoxy radomes. (b) Effect of radome slope on miss distance. (c) Radome slope. (d) Boresight error and aberration angle.

given radome slope as defined in figures 6c and d, it is essential to get a minimum aberration angle, i.e., the angle between the line of sight (LOS) to the actual and the line of sight to the apparent target positions. To realize this, it is essential that the right choice of radome material, thickness profiling and antenna positioning be made. This is an example of how the electrical design drives the overall missile seeker head design.

3. Aerospace vehicle integrated design

In §2, the interaction of subsystem level design packages has been discussed for three design cases, viz., aero-propulsion, control-structure and electrical-structural design. In an integrated design approach for an advanced aerospace vehicle, 6 individual design modules with the system constraints as inputs along with the required data base have to be built, and as many as 6 interface design modules are to be integrated with the interactive integrated design (core) package in addition to the weight and cost modules. The most important additional links which have to come in are the designers' experience and expertise in design. Can they be converted into realistic algorithms? These need to be in the form of a design database so that individual design software packages can be made to communicate with each other through the interface design modules and the interactive integrated design module. The interactive integrated design module shown in figure 7 removes the constraints normally introduced by individual design modules like aerodynamics, structures, control and guidance systems through interface using major interface design modules. An interactive integrated design approach will

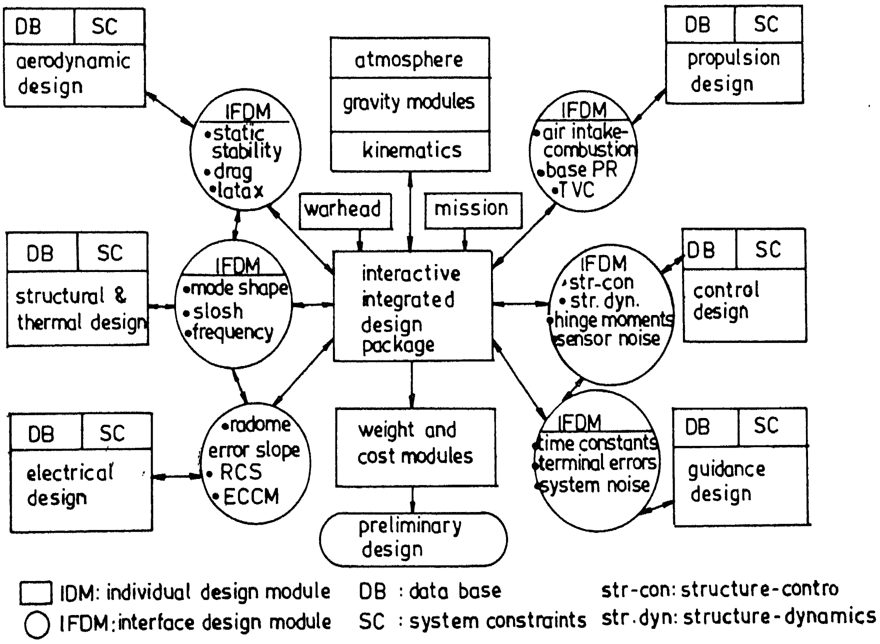

Figure 7. Aerospace vehicle integrated design – an outline.

bring out a reduction of design cycle time to one fifth its value, and at the same time, the design will be built on experience without losing any of it.

The interactive integrated design approach requires an extensive computational effort and sophisticated computer facilities covering the mainframe system, computer-aided design and drafting (CADD) system, parallel processors etc. The computer network for an integrated design approach is presented in figure 8. In this network, the mainframe system will have interactive terminals through a network processor. The kinematics and the interactive design interface modules are housed in this system. The network processor is interfaced with a CADD system with an ethernet for as many as 18 CADD servers. Each CADD server is provided with 4 disk packs of 500 MB storage space each and also with 8 user work-stations. The subsystem designs are generated in the CADD centre which has an interactive graphic display. Parallel processors are also interfaced with the network processor of the mainframe system through a front end processor and they are utilized for major number-crunching operations that are normally required for aerodynamic, combustion and structural analysis. Parallel processing of major individual design modules will help to bring down the computational delay on the mainframe system and also on the CADD system. Communication is also established between the parallel processor and the CADD system through the mainframe system. Such a computer network facility is an essential requirement for an integrated design approach. In the Defence Research and Development Laboratory/Defence Research and Development Organisation the methodology for an interactive integrated design approach has been evolved with a two-year programme for the integrated design package using the above scheme.

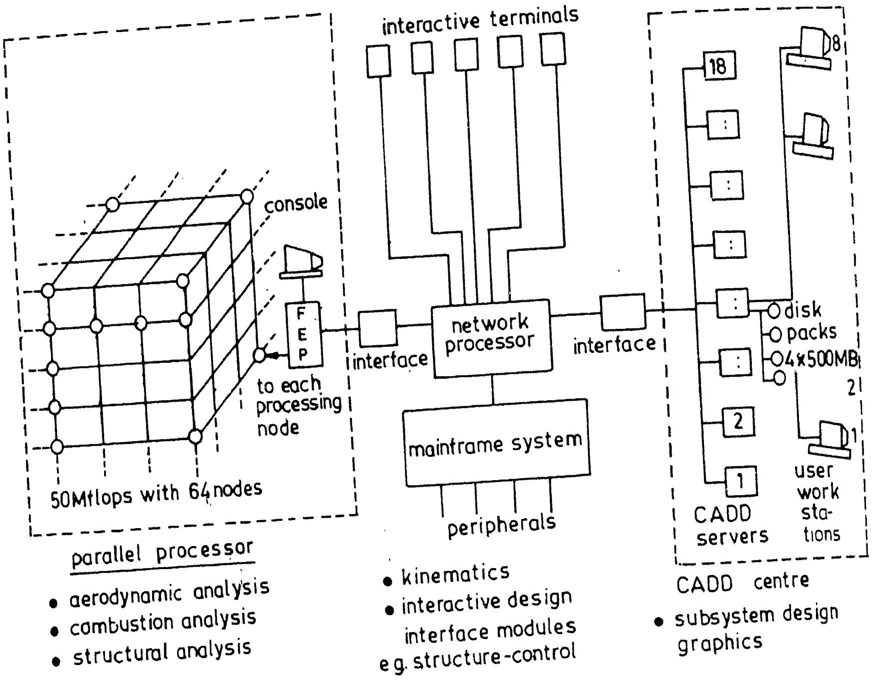

Figure 8. Schematic of a computer network for interactive design.

4. Conclusions

A conventional design approach for the subsystem of an aerospace vehicle results in a long design cycle time because of sequential and iterative design steps. Also, existing methods introduce constraints into the designs. Three examples project the need for an integrated design approach where interfacing of more than one subsystem is involved. An interactive integrated design approach is configured along with a computer network involving the available CADD Centre and mainframe system, and a proposed parallel processor computer.

This note has been prepared based on detailed discussions with designers in various areas of technology. We are particularly thankful to Dr Annapurna, Shri N R Iyer, Dr Subhash Chandran, Dr J Gowri Krishna, Dr K Neelakantan, Shri N V Kadam and Shri A Sivathanu Pillai for their assistance.