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INTEGRATED AERODYNAMIC DESIGN AND ANALYSIS OF LAUNCH VEHICLES

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ABSTRACT

An integrated aerodynamic design and analysis procedure for launch vehicles which incorporates engineering prediction methods, historical knowledge, and corporate memory into a knowledge-based system is described. The objective is to provide an economical means to conduct the aerodynamic design and analysis of future launch vehicles to minimize the risk of aerodynamic-induced failures. The method will provide a guide to the aerodynamic-related information required during the conceptual and preliminary design stages. In addition, the user will have access to historical information on similar launch vehicles, the ability to set up geometric characteristics, and a capability to predict preliminary aerodynamics of simple launch vehicles. The method includes a number of searchable databases containing technical references on launch vehicle aerodynamics, engineering experiences and anecdotes on launch vehicle programs of the past, and information about various launch vehicles. The method can be used as a stand-alone tool for traditional design approaches or as an integral part of a multidisciplinary design method. It has archive capability, and it can be updated with new information as desired by the user.

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INTRODUCTION

A primary mission goal for NASA and the aerospace industry is to design, develop, and maintain high quality and reliable space launch systems at less cost.[1] Although aerodynamics is only one of the many disciplines required to successfully design a launch vehicle, if the aerodynamic design and analysis procedure can provide accurate and reliable aerodynamic characteristics during all phases of the design cycle more efficiently at less cost, there will be a positive influence on the design process. Reduced risk, lower number of design cycles, more efficient design cycles, and ultimately, lower vehicle design costs will result.

New entrepreneurial companies are being formed to design one- and two-stage-to-orbit reusable launch vehicles (RLV) and more traditional expendable launch vehicles (ELV) that use state-of-the-art and off-the-shelf technologies. Of necessity, these designs are unique and sometimes unusual, and most of these vehicles are configurations without a track record of success nor a backlog of experience in their flight characteristics.

The experienced designers and analysts who learned from the successes and failures of the 1960s and 1970s are leaving the industry as a result of retirement and downsizing; thus much of this corporate memory and experience has the potential to be lost.[2] In addition, many of the younger engineers who have experience with the modern computational methods do not have experience in evaluating the accuracy of the flow physics provided by the advanced computational fluid dynamics (CFD) methods. Without the necessary mix of talent and experience, the new companies may find it difficult or impossible to build a launch vehicle able to perform the missions needed. One possible result is a number of new vehicles which simply cannot carry out the launch capabilities promised. An even worse result is a repeat of past failures with the associated increased costs and lost confidence in the new vehicles. This latter result is not only bad for the company in question, it is bad for the launch industry as a whole.

The aerodynamics design and analysis system called LVX (Launch Vehicle eXpert) has been developed to assist the launch vehicle designer in the analysis and evaluation of the aerodynamics of new launch vehicles during all phases of the design cycle, but it has primary application during conceptual and preliminary design.[3] The objective is to increase engineering efficiency and reduce development costs through a reduced number of design cycles and more timely interaction with other disciplines needing aerodynamic information. Finally, LVX has as a primary goal to reduce risk in the aerodynamics of new launch vehicles by making past experience accessible for new designs.

BACKGROUND

The development of LVX is based in part on NEAR's experience in the computational and experimental aerodynamic design and analysis of several launch vehicles. This work has been conducted for new companies without a history of success in this area. For example, NEAR provided the initial aerodynamics for the Orbital Sciences Corporation's Pegasus[4] and Taurus launch vehicles before Orbital had accumulated experience and established a history as a successful launch provider. NEAR also developed the initial aerodynamics for the concept studies for the early X-34 vehicle. In an extensive integrated computational and experimental program, NEAR did the aerodynamic design and analysis for the Kistler Aerospace Corporation's K-1 reusable launch vehicle.[5,6] In a similar combined computational and experimental aerodynamics program, the preliminary aerodynamics database was developed on the BA-1 and BA-2 expendable launch vehicles for Beal Aerospace.[5] Currently, NEAR is providing analytical aerodynamic analysis for the conceptual design of the Kelly Space and Technology 2nd Generation Reusable Launch Vehicle.

Concurrently with the above aerodynamics design and analysis tasks, NEAR was working in the information technology and knowledge-based system area to identify efficient ways to develop and search information databases for many different technology areas. For example, NEAR's CFDexchange was developed to capture and store CFD code usage and procedures and match CFD technologies with engineering applications.[7] This involved database design to store problem descriptions, available technology information, and calculation results, and more importantly, it involved the retrieval of information through sophisticated search capabilities. This database stores an archive of the configurations and flow fields solved, the CFD technologies used, the computational and labor resources required, and the results for previous calculations. In additional work, a scheme was devised for inserting new CFD calculations into the database automatically, and for compiling data from related runs which could then be viewed within a multidimensional design space.[8]

The goal for LVX is to combine expertise in launch vehicle aerodynamics with capabilities in information management to develop a practical tool for the aerodynamicist to employ in the design analysis of new launch vehicles. Useful and hard-to-find information is identified and collected in the system to create an online knowledge base of aerodynamics of launch vehicles. Information technologies are used to assist the system user in retrieving applicable knowledge that will help in the design. The method can be used as a stand-alone application for the aerodynamics discipline, to be run off-line to analyze and evaluate a number of potential configurations during conceptual and preliminary design. The method also has the potential to be used as the aerodynamics module in a multidisciplinary design method as illustrated in the simplified sketch in Fig. 1.

TECHNICAL APPROACH

LVX is made up of a collection of searchable databases with information linked together across these databases. As illustrated in Fig. 2, LVX has three major paths available to the user; (1) design assistance, (2) engineering analysis capability, and (3) database maintenance. Each of these applications has differing requirements.

In the design assistance area, the objective is to collect information in the form of published documents, personal experiences, aerodynamic data, and data on previous vehicles into a searchable database. Much of this information has been stored in disparate locations, but LVX makes it easily available to users in a single location. The engineering analysis capability permits the user to set up simplified geometries and perform first-order aerodynamic analyses. At the same time, links are made to pertinent information on similar configurations stored in the databases. The database maintenance is necessary to permit the user to update the various databases as design information advances over time.

The following paragraphs detail the various components of LVX shown in Fig. 2.

Keywords

It was decided early in LVX development that a hierarchical structure would be used to model the knowledge stored in the database. Each node in the hierarchy is represented by a keyword that describes a topic. This model allows the information stored to be linked in a logical fashion, which assists in both the knowledge acquisition and the knowledge retrieval mechanism. The keyword topics were chosen from several sources: NASA-assigned descriptors used to document relevant technical reports and papers, terms from the NASA Thesaurus, and additional terms that were identified from conversations with aerodynamics experts. This resulted in a standardized LVX-specific list of keywords.

LVX contains a database of relevant publications, and these typically are assigned keyword descriptors by NASA. However, since LVX's keywords are not always the same as those used by NASA indexers, it was necessary to translate many of NASA's terms into LVX's keywords.

Aerodynamics Experience

LVX is built around an aerodynamic knowledge base which includes design rules and engineering rules-of-thumb for launch vehicles. This information has been obtained from a number of sources including historical data reports and interviews with active and retired launch vehicle design experts from NASA and industry. The design rules and comments from these interviews are included in a database which includes links to other design information associated with specific configurations, and where possible, to published documents.

The interview process was conducted at several NASA centers, and it was accomplished with both individual and group interviews. Each knowledge acquisition session was taped and subsequently transcribed. The transcriptions were later edited for accuracy, grammar, and completeness. A knowledge engineer worked from the edited transcripts to glean the individual pieces of information or knowledge data. In the original database, no specific piece of information was attributed to any specific individual in an effort to keep the interviewees open and unselfconscious.

This information can be updated to include new and corrected information.

References Database

The system also includes a database which contain references to published reports. This extensive database contains more than 2,100 citations to technical documents on launch vehicle aerodynamics and data. Keywords are ascribed to each document, and these keywords are used in the search and retrieval process.

The documents were identified through a number of sources, including (1) a list of relevant papers and reports collected by the authors in the course of past work on launch vehicles, (2) citations from survey papers and other work of prominent researchers in the field, (3) a search for applicable reports in the NEAR Technical Library, and (4) a search in the NASA Reconplus database using selected keywords.

In an effort to make this database as useful and relevant as possible, each citation was checked by an engineer to be sure only appropriate technical information was included. When in doubt about the quality of a citation, it was included in the interest of completeness.

Geometry Description

In the design portion of LVX, the user can set up a simplified model of a new configuration using a component buildup method. As the user specifies the various components, nose shape, body shape, wing and/or tail geometry, and other items, the code automatically assigns appropriate keywords to a list. This list can be used to search for similar designs and key references from the database. The user is free to add or delete the keywords associated with a particular geometry.

The user can also import a more detailed geometry from a geometry package outside LVX. This can be used to compare with the simplified internal model, and it can provide some guidance as to how the simple component model can be improved.

Analysis Methods

The system includes analysis codes of varying fidelity that the user can call upon to analyze the design under consideration. Several codes can be run directly from the system, and the results are immediately available for analysis and archive purposes. Every aerodynamics code cannot be included in the system, but an interface can be provided so that the user can run any desired code outside the boundaries of the system, and the results can be imported into LVX for analysis and archive purposes.

LVX can create input files for two codes, R1307[9] and Missile DATCOM[10,11] and work is in progress to add APAS[12,13] to the list. R1307 is a linear aerodynamics, slender body theory method used to calculate aerodynamic characteristics of wing-body-tail combinations. Missile DATCOM uses both analytic and empirical methods to calculate aerodynamics of simple configurations. APAS is based on linear potential theory at subsonic and supersonic speeds, and at hypersonic speeds it uses impact solutions. Both R1307 and Missile DATCOM are easy to set up and run, but they are constrained to address conventional geometries, such as geometries with axisymmetric bodies and wings without winglets or camber. APAS can handle arbitrary geometries but requires more detail in the geometry input and added user effort in running the code.

The user creates the input for a code by specifying the geometry with components and setting the flow condition and reference conditions. The user then saves the input to disk, and the analysis program is run external to the LVX system. The computed results are brought back into the LVX system. The archiving of results in this manner automatically builds a history of the project aerodynamic results.

Aerodynamics Database

The aerodynamic database can consist of both experimental data and computational analysis results. Currently, LVX has experimental data included for the X34 and Shuttle. The user may expand this database by adding data and results. When adding aerodynamic information to the system, the user tags the data with the appropriate descriptor and content keywords. The descriptor keywords describe or identify the data; for example, supersonic X-34 CFD analysis. The content keywords describe the characteristics of the data; for example, normal force and pitching moment vs angle of attack and Mach number. ASCII data files may be imported into the system as either formatted or unformatted files. The formatted input organizes the data into 3-D databases delimited by zones, rows, and columns. An example would be an experimental data set organized so the zones represent Mach numbers and the rows and columns represent angles of attack and aerodynamic coefficients, respectively. With the data in this format, LVX can manipulate it. The only manipulation requirement currently planned is for LVX to export the user required data in a spreadsheet format. This may be expanded in future work. When the data are unformatted, the user may view it in LVX and export the information unchanged.

The aerodynamic databases in the system can be modified by the user to include both experimental data and computational analysis results as they become available during the configuration design; thus the system can be used to archive aerodynamic results as the new design evolves through the design process.

Design Iteration

A design iteration involves defining the characteristics of the proposed design, accessing expert conclusions about the viability of the design, viewing comparable vehicles in the database, and perhaps running an analysis code. The user may decide to iterate on the design to remedy potential problems and/or improve on the original design. In some cases LVX may suggest courses of action to improve on the design, or the explanatory facility may indicate the source of problem areas. The user has the option to repeat the design process with modifications to the original design. The results of each design iteration can be stored in the database.

Help Features

Help features for the system currently include code and keyword descriptions. The aerodynamics code descriptions provide the user with guidance in selecting the proper code for an analysis. The codes are categorized by their analysis fidelity; for example, engineering, intermediate, and CFD. Strengths and weaknesses, advice for applications, and code availability are given.

A manual and tutorial for the use of LVX will be included.

DISCUSSION

LVX has been distributed in a beta version for review and comment. The following figures show screen shots of this version of LVX.

Fig. 3 shows the search window. The keyword X-34 has been selected from the hierarchical keyword list on the left. The text boxes at the bottom of the window are provided for title and/or author searches. The scope of this search includes all four databases; References, Vehicles, Data, and Facts as indicated by the checked boxes at the top.

Figs. 4, 5, and 6 show the results of the search. In Fig. 4, information in all four databases was found in this search as indicated by the tabs at the top labeled References, Vehicles, Data, and Facts. The Parameters tab is simply a list of the search parameters. Fig. 5, the Vehicles tab, provides a description of the vehicle with a link to a photograph. Fig. 6, the Data tab, shows a list of the experimental datasets on the X-34 vehicle which are currently stored in LVX.

The user may save the results of a search to an ASCII file, and the information may be hyperlinked to related information.

Figs. 7 and 8 show the design window with a simple configuration with an ogive nose and a straked wing. The window's lower left pane is used for the keywords associated with the geometry. Listed in the right window pane are the modes that can be selected to specify keywords; Reference Conditions, Geometry, Flight Conditions, Mission Characteristics, and Keywords. These multiple selection modes can be used simultaneously. At the top of the window, just below the menu bar, are the various components that can be selected to build a geometry. In the upper left window of Fig. 8 is a list of the current geometry buildup, and selecting a component, such as the nose, will provide an edit window for changing the configuration parameters or the nose type.

Similar windows are available for creating the input files for the engineering analysis codes. These can be saved to disk for use during the running of the code external to LVX. Two codes, R1307 and Missile DATCOM, are set up for execution by LVX. For other codes, such as APAS or other higher level codes, the user must perform the action to execute the codes. The results can be imported back into LVX through the archive interface provided by LVX.

LESSONS LEARNED

There were a number of lessons learned in each part of LVX development. Some were expected, but a number were unexpected.

Some of the interesting problems which occurred in the knowledge acquisition process involved directing the interviews and keeping the discussions on topic. The interviews were taped and transcribed for use in sorting out the relevant facts. One of the interesting aspects of the interview process was the difficulty in obtaining relevant information from expert interviews. Often the pieces of information were unconnected and incomplete, and some follow-up was necessary to insure the accuracy of the data. It was also necessary to sort out proprietary information from the interviews.

Another problem was creating appropriate links to other information in the database. Rules and facts are included without attribution; however, this creates a problem evaluating the quality of the information. The user should have some means to assess the accuracy of the data. This approach may need to change to include some source information attached to each item in the knowledge database.

The generation of the technical documents database, although seemingly straightforward, provided a number of unanticipated problems. One search produced more than 2,600 citations which needed to be examined to eliminate inappropriate documents. It was during this process that one of the major problems was discovered, and that involved incorrect, inconsistent, and missing information in the citations. In addition, it was surprising that the reference lists in a number of published reports were found to have many errors and inaccuracies. In fact, in some cases it was not possible to locate cited references from the information provided in the report/paper reference list; that is, truncated titles, misspelled and missing authors' names, and incorrect dates.

Because of the various problems with the citations, it was necessary to make the corrections to the individual citations by looking at them one at a time. This was a very labor intensive process and extremely time consuming. Unfortunately, no other approach could produce the quality of database required for LVX.

Similarly, for the aerodynamic analysis codes portion of LVX, it was necessary to be aware of proprietary, licensing, and ITAR requirements. This is the reason that more codes are not included and that provision was made to run codes outside of LVX. The same problem occurred with the inclusion of experimental data.

CONCLUSIONS

A prototype system has been developed to demonstrate the aerodynamic design and analysis procedure. The final LVX system described is still in the testing phase, although most of the databases and interfaces are complete.

The rules database generated from numerous interviews with active and retired launch vehicle aerodynamicists is not complete, and this database can be expanded with current information as it becomes available.

The LVX system is intended to capture aerodynamics design data, yet several factors prevent the databases from being complete. One problem is the issue of proprietary data. The other issue is that collective knowledge on aerodynamics design increases over time. For these two reasons, LVX has the capability for the users of the system to add their own knowledge to the databases. Thus, users can add proprietary information that pertains to their projects, and they can add new information as it is generated over time. This facility allows LVX to remain current and relevant.

ACKNOWLEDGMENTS

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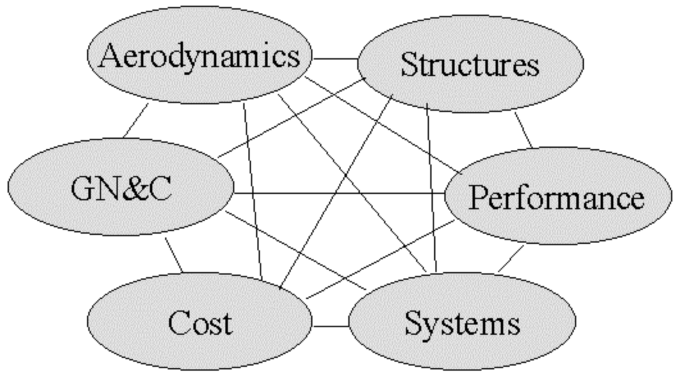

Fig. 1.- Sample integrated design process.

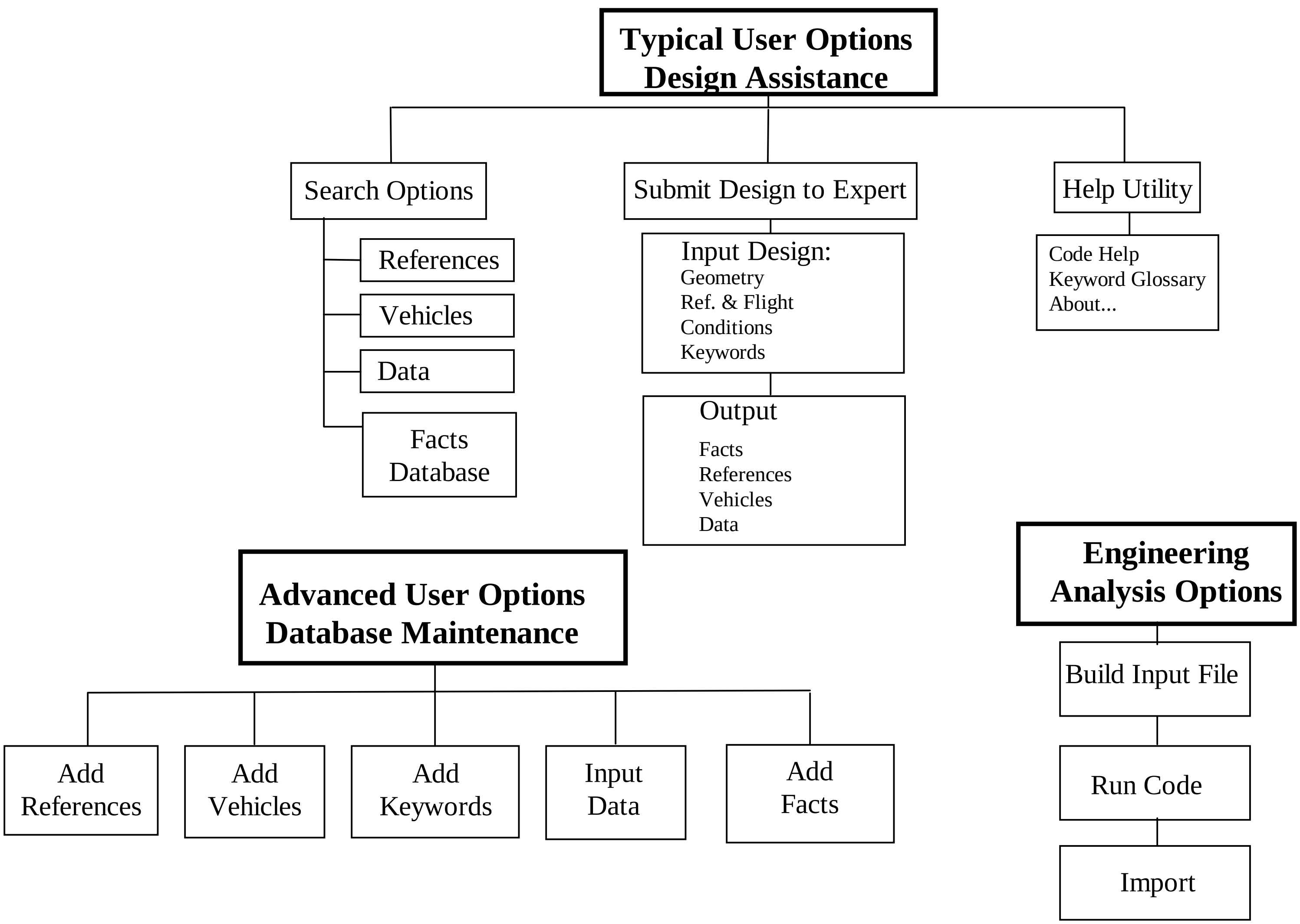

Fig. 2.- Launch Vehicle eXpert System

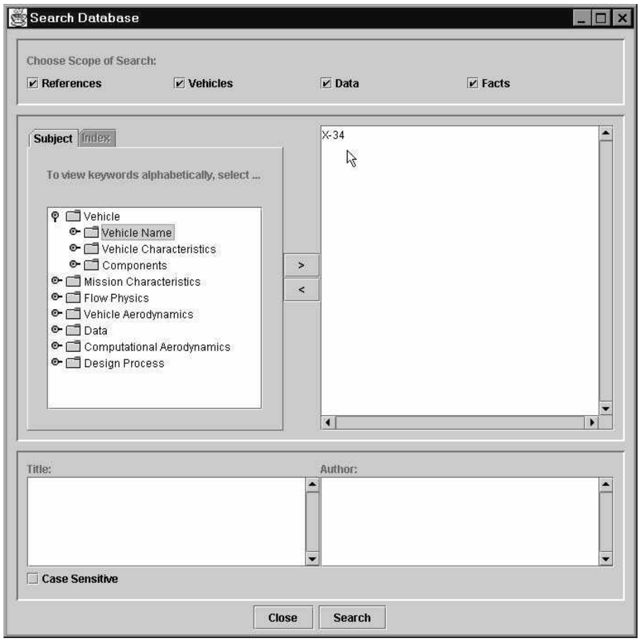

Fig. 3.- LVX search window.

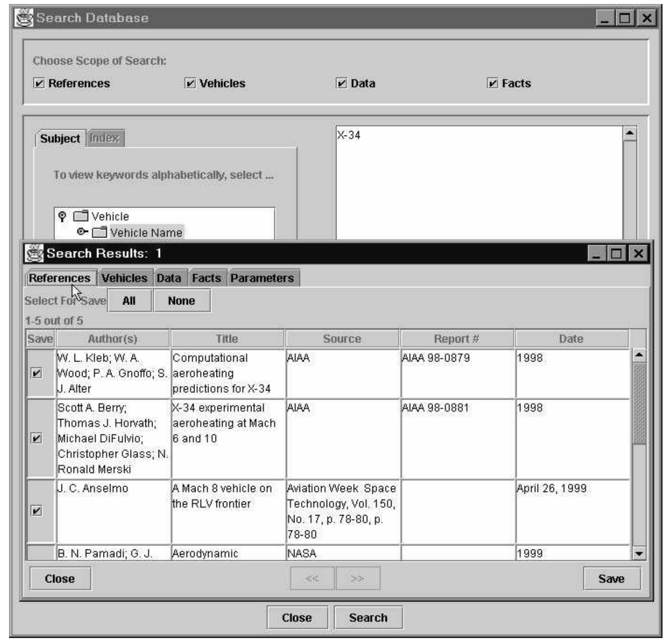

Fig. 4.- Search results; References.

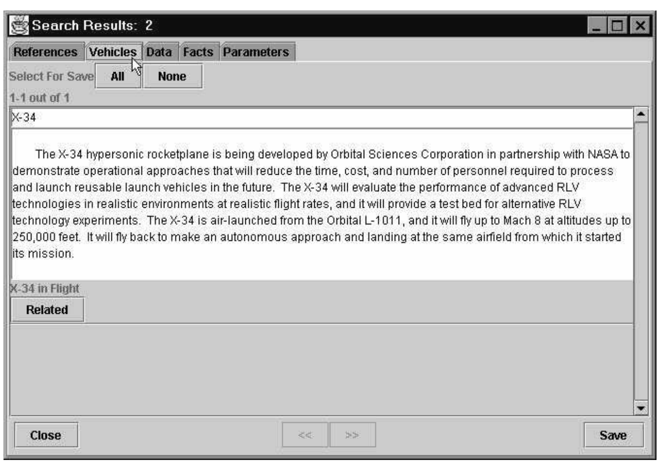

Fig. 5.- Search results; Vehicle Description.

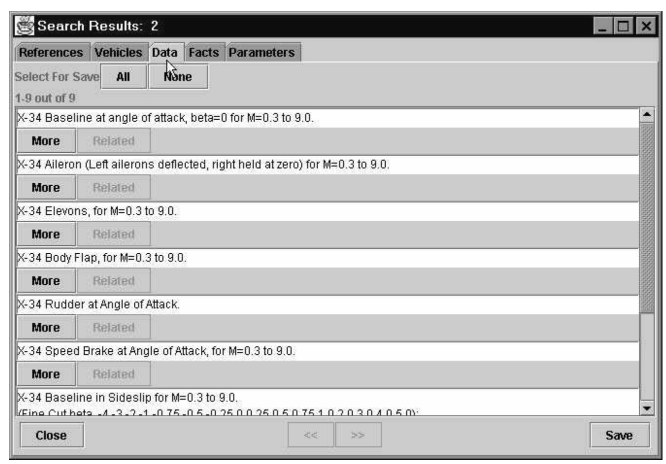

Fig. 6.- Search results; Experimental Database.

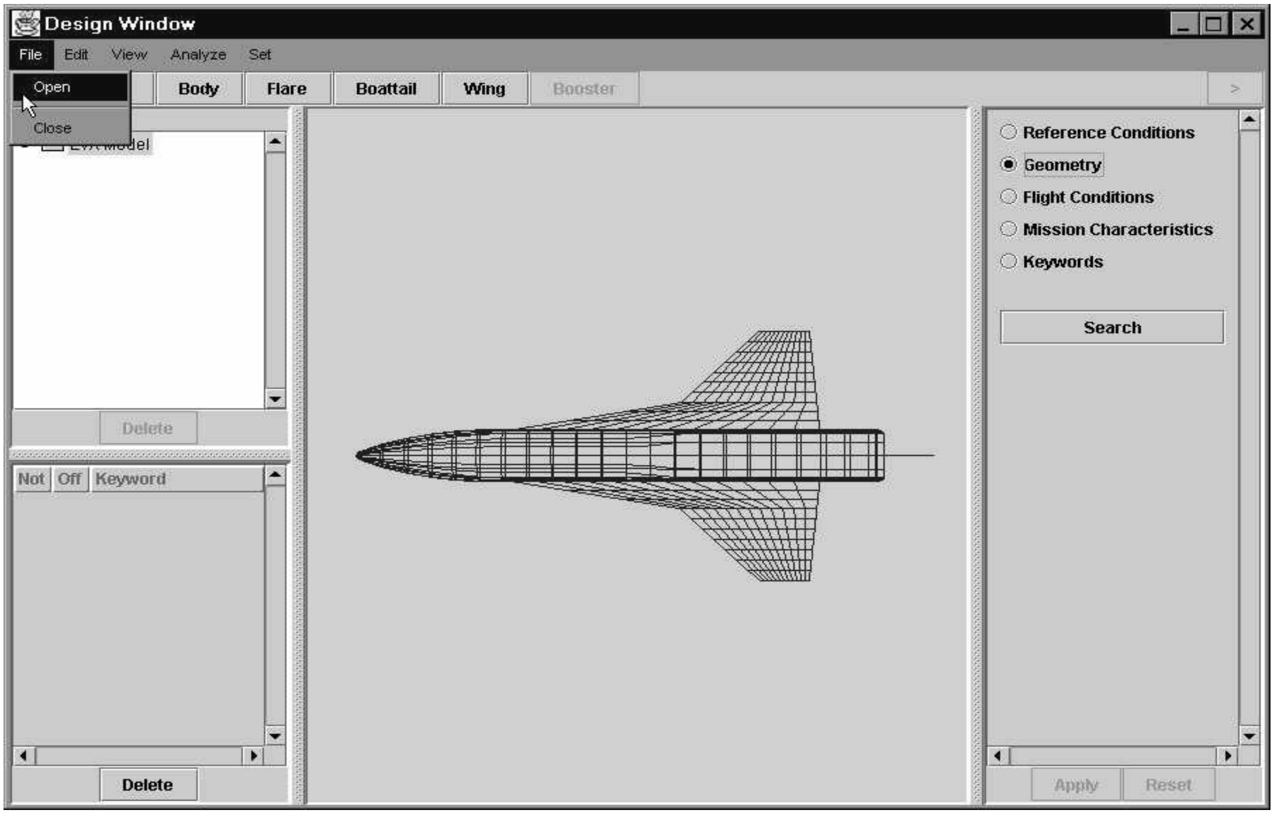

Fig. 7.- Design window.

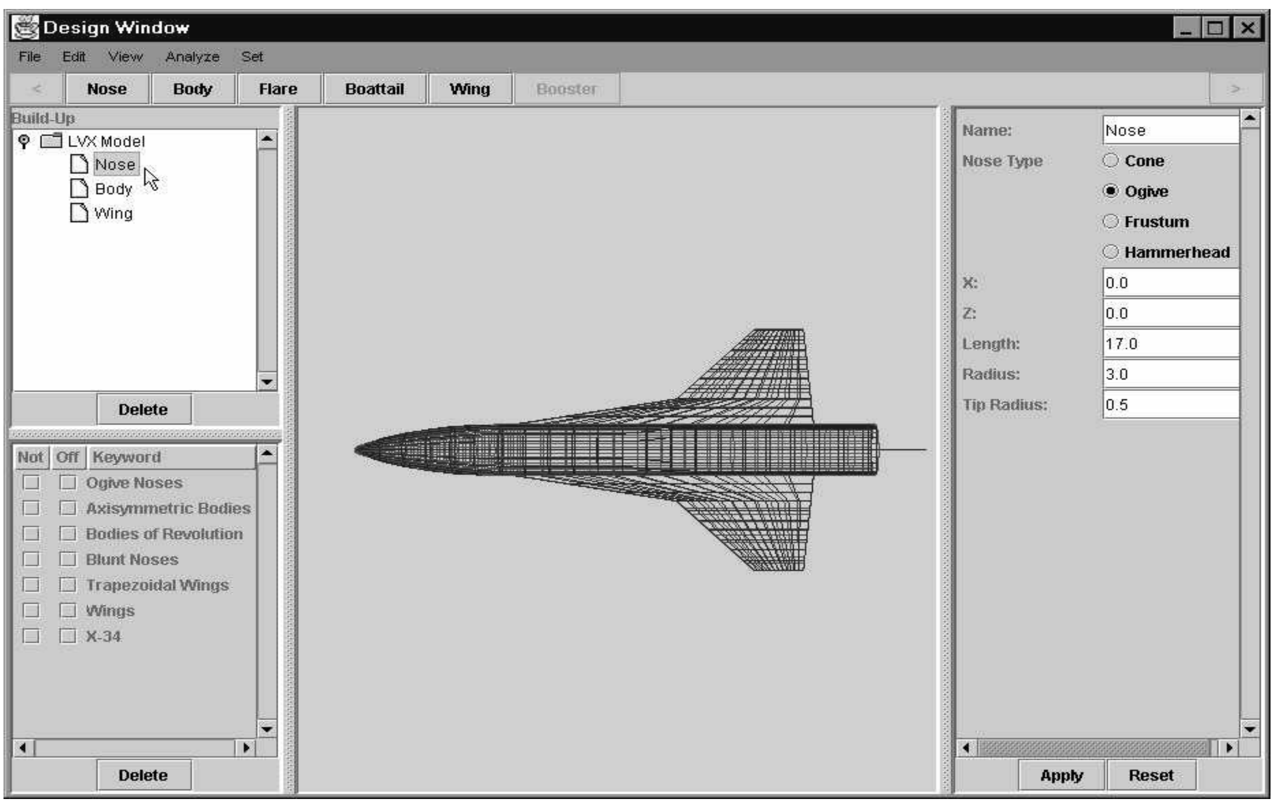

Fig. 8.- Design window; configuration components.