A BEST PRACTICES SYSTEM FOR REDUCED UNCERTAINTY IN CFD

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Abstract

A best practices expert system for CFD users (BPX) which provides expert knowledge and guidance in the use of CFD codes is described. The goal of this system is to enable CFD users to obtain high quality CFD solutions with reduced uncertainty and lower cost for a wide range of aerospace flow problems. The software includes specific guidelines to assist the user in problem definition, input preparation, grid generation, code selection, parameter specification, results interpretation, verification, and validation. The method couples knowledge databases of expert information with specific guidelines and standards for individual codes and algorithms.

1 Introduction

CFD plays an essential and ever increasing role in the design and analysis of advanced aerospace vehicles. Any time and cost savings in the CFD process will lead directly to cost reductions in the design and development program. To increase the efficiency of the CFD process, unnecessary CFD runs must be eliminated, errors must be minimized, and past mistakes must be avoided. Many problems with CFD solutions can be traced to inexperienced users producing results with software they do not understand [1]. The user has a critical role in current CFD processes, and this produces significant variability in the quality of CFD results because of differing concepts of best practices among users.

For purposes of the present work, the concept of "Best Practices" is defined as a set of specific guidelines to assist in grid generation, the selection of the parameters that control the CFD code execution, the assessment of the resulting solution, the identification of abnormal results, and the means of correcting the solution. The best-practices guidelines function as a practical set of instructions, a check list for CFD users, and a tutorial for novice users or experienced users unfamiliar with a specific code. For many applications, a definitive set of best practices does not exist, but an accepted set of recommended practices are available based on the experience of expert users. These rules and guidelines, which may change with time, need to be available to CFD users.

The best-practices system called BPX (Best Practices eXpert) provides expert knowledge in the use of CFD codes to users, developers, and technology managers[2]. The goal of the system is to enable CFD users to obtain high quality CFD solutions with reduced uncertainty and lower cost for a wide range of flow problems. BPX includes specific guidelines to assist the user in problem definition, code selection, input preparation, grid generation, parameter specification, results interpretation, verification, and validation. BPX couples knowledge databases of expert information with specific rules and guidelines for individual codes and algorithms.

A common research goal in CFD is to make CFD less of an "art" and more of a "science." The artistry of CFD is in the expertise and diligence of the CFD engineers who control the countless details that go into a typical CFD calculation. These skills are acquired over years of schooling and experience. The science of CFD includes the specific knowledge, guidelines, and standards for obtaining a successful solution and a checklist of properties to use to verify a solution. BPX is the bridge between the art and science aspects of CFD. It was designed to provide a means by which the knowledge of the expert user could be exploited to establish standards for the use of CFD codes by both the expert and novice. These standards ensure that all reasonable steps have been taken to achieve the highest practical accuracy of a CFD solution. Ultimately, the system of best practices will provide a means for the quantitative estimation of the uncertainty in a CFD solution.

2 Background and Objectives

The application of and search for best practices in CFD is not new, and a number of examples are presented in References 3 through 11. Some of these approaches require a skilled CFD user to interpret the results and implement corrective actions. It is the goal of BPX to assist the user with this capability.

The objective of BPX is to provide a state-of-the-art capability for CFD analysis which can be broadly applied by users interested in (1) improving the accuracy and reducing the uncertainty of CFD results, and (2) reducing the time and cost associated with CFD applications. Meeting this objective requires a means to provide the user with easy access to both general expert knowledge and specific advice on the nuances associated with the use of specific codes. A software framework is essential, given the quantity and variety of information available, and it is expected that such a system will be intuitive to use, be of benefit to users with a wide range of experience, and be generally helpful by anticipating problems using frequently asked questions and lessons learned.

3 Technical Approach

The goal of the technical approach is to develop a system of best practices that will provide state-of-the-art capability for CFD analyses to users of all skill levels. The core of best practices consists of the expert knowledge of experienced CFD developers and users [12]. This expert information provides the guidelines for successful setup and execution of CFD calculations, problem diagnosis, and correction of the solutions.

BPX, as described in this paper, is a framework, designed to support a variety of knowledge-based components, which can be expanded and populated over time. In the initial version, the information included is heavily weighted toward the use of one CFD code, OVERFLOW, because of the quantity of information available to the authors and the specific interests of the sponsor. The focus of BPX is also weighted toward external flow aerospace applications, again because of the necessity to limit the scope to fit the resources available. The objective is to demonstrate the approach to best practices with BPX and to build in the flexibility to expand the framework to include multiple codes, broader applications, and other technical areas at a later time.

The development of the BPX system is based on the approaches successfully used for two integrated aerodynamics design and analysis systems called LVX (Launch Vehicle eXpert) [13,14] and RSX (Rocket Sled eXpert) [15,16]. These systems incorporate an expert knowledge database, historical design guidelines, and a references database into a knowledge-based system, which is also coupled with legacy analysis methods. The development of BPX was leveraged by the lessons learned during LVX and RSX software development.

3.1 System Requirements

To meet the BPX objectives, the following requirements were used to guide development of the system:

- Provide an intuitive process for general acceptance by the CFD community.
- Demonstrate ease of use for users of all skill levels.
- Provide information appropriate for CFD users to achieve more reliable CFD results with less effort.

- Provide a rational subset of procedures and expert knowledge that should be followed to achieve the required accuracy from CFD.
- Evolve with advancements in CFD algorithms and codes.
- Employ a framework for best practices applicable to all algorithms and solvers that developers and/or users are willing to support.
- Permit individual users to customize details of best practices to support specific needs and provide for proprietary versions of the system.
- Provide a self-critical system by noting the relative confidence in specific guidelines and characterizing the aspects of CFD practices that are poorly understood.

3.2 System Components

The BPX software is made up of the following components:

- Graphical User Interface (GUI)
- Expert Knowledge Repository
- Rule-Based Expert System
- Technical References Database
- CFD Process Breakdown
- Search and Cross-Reference Capability
- User Guidelines and Alerts
- Code Input Verification
- Frequently Asked Questions
- Tutorials
- Sample Grids

3.3 BPX Framework

The framework for the BPX system is shown in Fig. 1. The system incorporates a rule-based expert system and an expert knowledge database that include the best-practices guidelines. A technical references database includes document citations for supporting information. The databases can be searched by the user from any point in the process. The CFD solution process is distributed between the twelve areas provided for the user to set up the details of the specific problem under consideration. The user has access to each process area at any time for testing and sanity checking.

3.4 Keyword Hierarchy

A hierarchical keyword structure is used to organize the expert knowledge, guidelines, and references stored in the databases. Each node in the hierarchy is represented by a keyword that describes a specific technical topic. The hierarchy is a convenient way to organize the information in the databases so that it is easily accessible for editing and maintenance. This model allows the stored information to be linked in a logical fashion, which assists in both the knowledge acquisition and the knowledge retrieval mechanism. There are approximately four hundred keywords in the current BPX hierarchy, and the user can add additional keywords as needed.

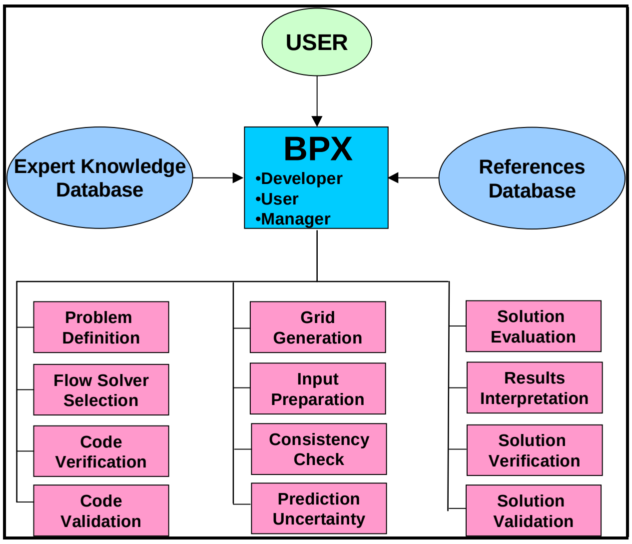

Fig. 1. BPX framework.

For purposes of illustrating the keyword hierarchy, the highest levels of the hierarchy are shown in Fig. 2. It is important that the keyword list be comprehensive and as complete as possible; however, the actual position or location of the topics in the hierarchy is not critical to the best-practices process. There are many links and connections between keywords at all levels in the hierarchy so that the interdependence between topics, for example, grid generation and flow conditions, is maintained without regard to their physical position in the hierarchy.

3.5 Expert Knowledge Database

The expert knowledge database is organized around the keyword hierarchy described above. Technical information was obtained from numerous interviews with expert CFD developers and users. The interviews were transcribed and checked for accuracy, and then the interviews were parsed into small packets or nuggets of information. Each nugget of information is tagged with one or more keywords and included in the database in the hierarchy corresponding to the primary keyword. The current expert knowledge database in its present form is approximately 100 pages long in a typical text format.

A separate database for the rule-based expert system includes specific information on the application of the CFD code OVERFLOW for a variety of flow problems. This information was gleaned from interviews with the developer and expert users and from a number of publications. Rules are included to address grid generation, selection of turbulence models, and other key steps in the CFD process.

A second feature of the expert knowledge in BPX is a list of frequently asked questions (FAQ) on the CFD code OVERFLOW which are based on actual questions received from typical users. It is anticipated that OVERFLOW users will be able to answer a number of common questions without contacting the code developer directly, thus relieving him of some of the time spent answering questions and providing support to users. This feature can be included for other codes for which information is available.

Manuals are included for all the CFD codes featured in BPX.

- **Physical Problem Definition**
    - **Configuration Definition**
    - **Geometry**
    - **Flow Characteristics**
    - **Results Required**
- **Mathematical Problem Definition**
    - **Governing Equations**
    - **Physics Modeling**
    - **Boundary Conditions**
- **CFD Solution Technology**
    - **CFD Codes**
    - **Algorithms**
    - **Verification**
- **Grid Generation Technology**
    - **Grid Types**
    - **Grid Quality**
    - **Grid Generation**
- **Validation**
    - **Experiment**
    - **Benchmarking**
    - **Error Control**
    - **Error Estimation**
- **Solution Generation**
    - **Code Usage**
    - **Solution Convergence**
    - **Grid Refinement**
    - **User Training**
- **Postprocessing**
    - **Procedures**
    - **Presentation**
    - **Feature Recognition**
    - **Solution Evaluation**
    - **Sensitivity Analysis**
    - **Interpretation**
    - **Knowledge Limitations**
    - **Statistical Analysis**

Fig. 2. BPX keyword hierarchy.

Another feature included is a tutorial on verification and validation. This information was presented as an AIAA Short Course by Dr. William L. Oberkampf of Sandia National Laboratories and Dr. Chris Roy of Auburn University. With permission of the course authors and AIAA, the slides from the short course are included as a tutorial to guide the user in the fundamentals of verification and validation. It is possible to include other tutorials in specific subjects so that BPX can be used as a training tool and as a means to archive the corporate memory [12] of the user organization.

3.6 References Database

The references database in BPX was created as the result of an extensive literature search of the open literature. This effort produced approximately 10,900 citations to technical references which have been included in BPX and tagged with the current keyword list. Other important technical reference documents were identified during the expert interviews. Some effort has been made to screen the references to keep the list to a manageable size; for example, most of the references included are for application to aerospace problems. Obviously, it is possible to expand this database to include information from other technical areas of interest.

4 Best Practices Expert System

An example of the use of BPX is shown in this section. It should be noted that some of the expert information shown is for illustrative purposes, and it may not include the level of detail that will appear in a final version of the method.

BPX anticipates user needs and makes decisions based on the direction the user takes in setting up a problem. The problem definition and options chosen, such as code selection, flow conditions, and configuration information, are used to provide guidelines for the user. Also based on these user decisions, BPX will provide references to documents which will give additional background information to the user. Therefore, the information shown in this example is dependent on the choices made in setting up the example, and some results are shown for the purpose of illustrating the contents of BPX windows.

The opening screen is shown in Fig. 3. User login can be controlled by a password.

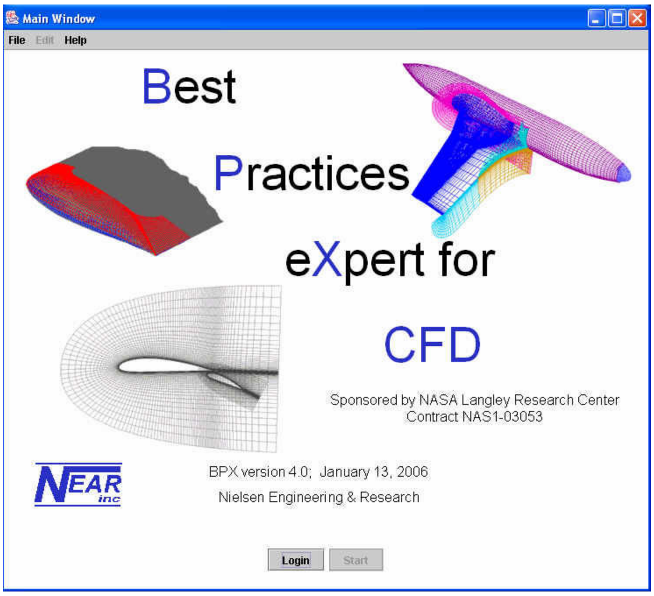

Fig. 3. BPX Main Window.

The Start window is shown in Fig. 4. The twelve major divisions of the CFD Process Tree chosen for BPX are shown in the upper left pane. The selection of these steps will lead to the display of panels from which the user can select parameters to define the problem under consideration.

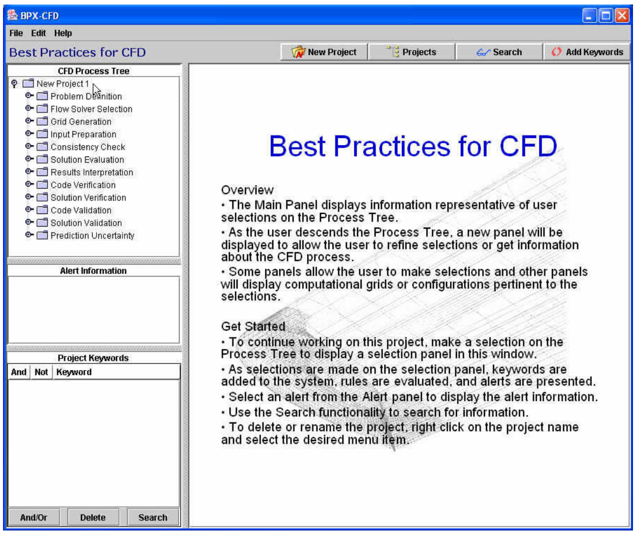

Fig. 4. BPX start window.

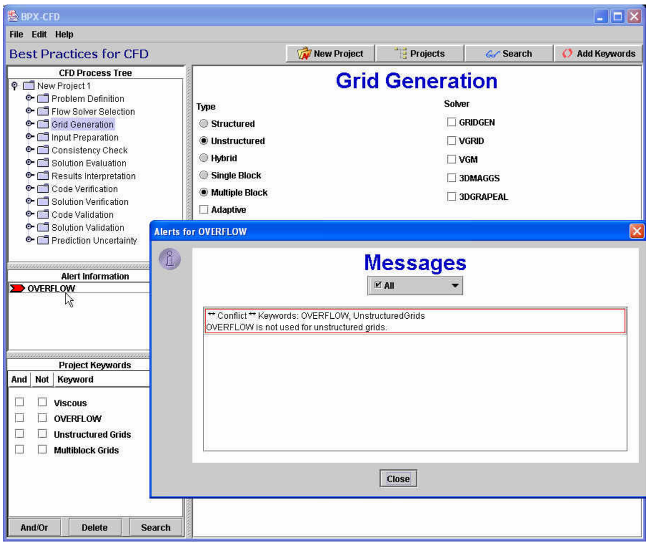

Fig. 5. BPX conflict warning and message window.

In this example, a number of selections have been made by the user to define the specific problem, and most of these choices are shown in the list of Project Keywords in the lower left pane of Fig. 5. These keywords are automatically selected by BPX based on decisions made by the user. Note that the problem specification at this point shows that a viscous solution using OVERFLOW with unstructured multiblock grids is desired. When the user selects the combination of OVERFLOW and unstructured grids, an alert message appears in the center left pane with a red conflict flag. Clicking on this alert brings up the message window which explains the problem; OVERFLOW cannot be used with unstructured grids. Changing the grid selection to Structured will cause the alert flag to disappear.

In the new window shown in Fig. 6, a number of user decisions have been made as indicated by the automatically selected keywords shown in the lower left pane. The problem has been focused on a single element airfoil at transonic speeds. Moving down the CFD Process Tree in the upper left pane produces an example grid in the main window where various regions are highlighted in color. Clicking in one of these regions, the upper surface shock location in this case, produces some grid guidelines in the lower portion of the window. In this example, it is noted that the grid shown is not sufficient to capture or resolve the shock wave on the upper surface. Note that the grid shown is for illustration purposes only; it is not a user-generated grid. Other example grids are available for wings and wing-body geometries.

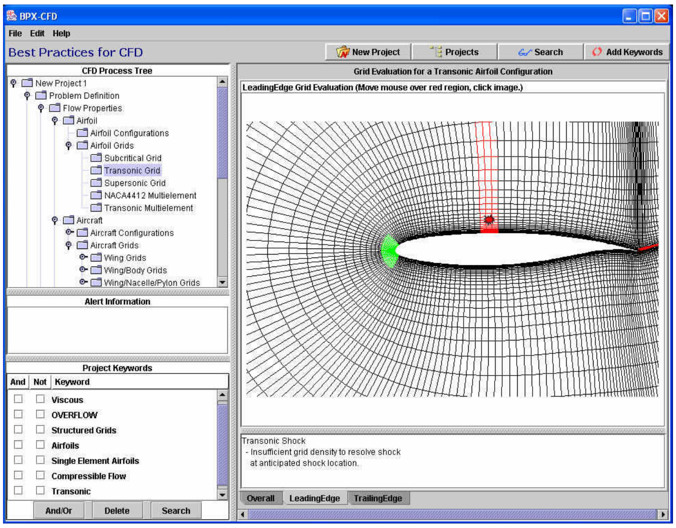

Fig. 6. Airfoil grid window.

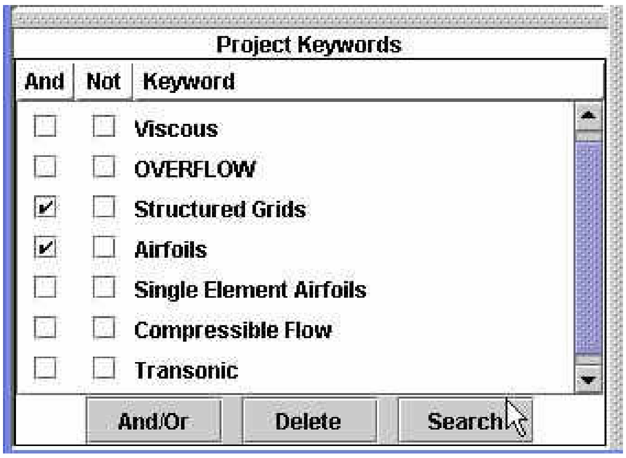

Fig. 7. Search window.

At any time in the process, the user can return to the Project Keywords pane and search for additional information as shown in Fig. 7. In this case, the user is requesting a search for all information and references on "Structured Grids and Airfoils." The results of this search are shown in Fig. 8.

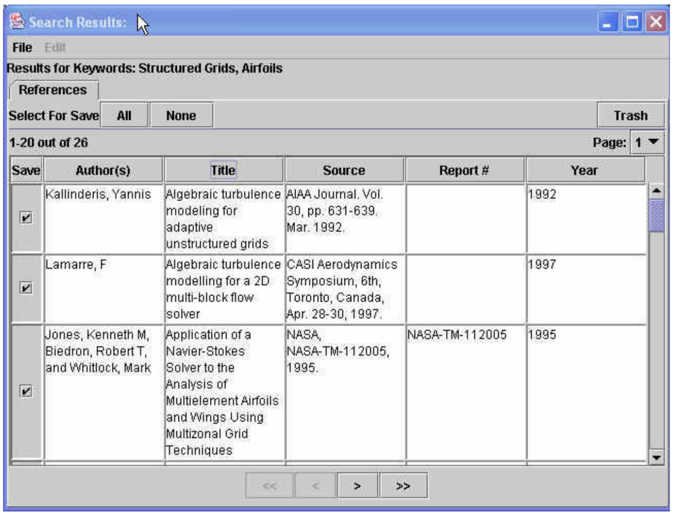

Fig. 8. Search Results window.

The keywords used in the search are shown at the top of the window, and the results of the search produced 26 references. The first three references are shown in Fig. 8; however, as with all search engines, the user must try multiple search techniques. For example, a search on "Airfoils" alone will produce more than 450 reference hits as well as 23 Technical Information nuggets. An example of two nuggets of technical information from the search on airfoils is shown in Fig. 9.

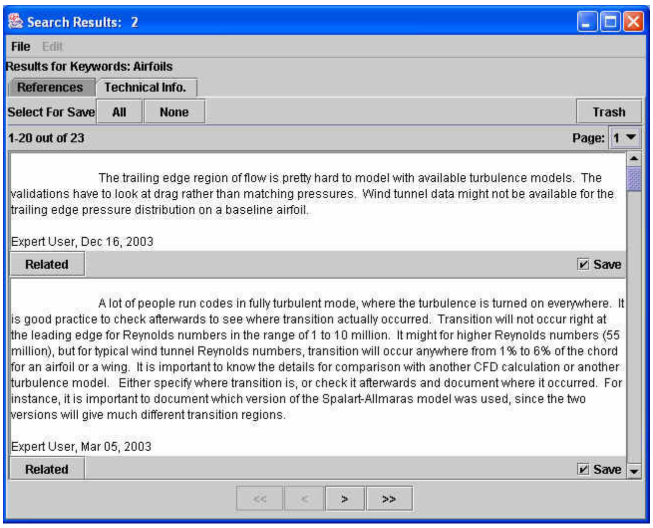

Fig. 9. Technical Information Search Results window.

There are many other features and capabilities of BPX that are not shown here because of space limitations. For example:

- Guidelines are provided for information, concurrence, cautionary, and conflict conditions to guide the user in the proper use of CFD tools.
- Three-dimensional computational grids are displayed in a graphical environment.
- Frequently asked questions are included in a searchable database.
- Manuals for CFD and grid generation codes are provided in PDF format when available, otherwise, a link to a web page supporting the code is provided.
- Multiple projects may be created and saved.

5 Concluding Remarks

An approach to a best practices system to assist CFD users in obtaining reliable CFD results with reduced uncertainty has been described. The rules and guidelines are based on expert knowledge obtained from the CFD user and developer community. Continued experience and advances in CFD technology can be added to future BPX systems. The BPX system may be used as a tool to assist the CFD engineer in making decisions that will lead to more accurate computational results in less time and at lower cost by reducing errors and unnecessary runs.

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