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AERODYNAMIC DESIGN, ANALYSIS, INTEGRATION, AND OPTIMIZATION TOOL FOR CENTRIFUGAL COMPRESSOR OEM

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ABSTRACT

While three-dimensional techniques are widely used in the turbomachinery industry, a mean-line approach remains at the core of multidisciplinary design and analysis. Combining rules of design, conservation laws, and experience permits narrowing down design options, outlining geometry, and evaluating results in an effective and consistent manner.

This paper reports on a project initiated by the original equipment manufacturer (OEM) to develop a versatile close-coupled stage design system for centrifugal compressor stages. This mean-line design suite is based on flexible system architecture including a combination of in-house and commercial analysis and design software modules. Inter-code data transfer and user interfacing are facilitated through a master spreadsheet and a commercial director integration program. Significant outputs available from this design system include rule-based solid models and selective flow path component optimization. Examples of both are presented in this paper.

This work was done as part of an undergraduate cooperative work-study program. The cooperative education program offers value to both industry and academia. The educational and commercial implications of this project are discussed.

INTRODUCTION

This paper presents two major aspects of the project. One is a technical description of the development of the novel integrated design suite. The other is the educational implications of this joint project for both the sponsor company and the participating undergraduate student.

The analytical portion of a typical aerodynamic design process for centrifugal compressor stages progresses from 1-D evaluation and concludes with a detailed 3-D (Computational Fluid Dynamics or CFD) analysis. This process usually begins with baseline geometry created or screened with the help of a 1-D design and analysis tool. This geometry typically includes an impeller with rudimentary blade definition and stationary components. The next step is to improve the impeller blade definition using a higher-level analysis program. The final step of this process consists of analyzing the refined geometry with a 3-D (CFD) analysis program.

As in many industries, the turbomachinery industry is under constant pressure to reduce the cycle time required to create or improve its products. This can most readily be achieved in the upstream design processes, where alterations are least costly and easiest to implement than in later manufacturing or testing phases. Figure 1 [1] clearly depicts the importance of streamlining early in the design process. This is the intent of the proposed close-coupled design system with integrated optimization and automatic solid model creation.

The importance of 1-D optimization early in the design process for centrifugal compressors is widely recognized [2], as well as the need for careful and precise geometric layout of all stage components. A mean-line code working in distinct design and analysis modes facilitates both of these functions [3].

Japikse [2] describes a commercially available multi-level software environment that allows the generation of final flow path geometry in CAD format. Another software package for compressor flow path design, described by Moroz et al. [4], is a single software environment incorporating stage aerodynamic analysis and preliminary design at 1-D to 3-D levels, capable of blade geometry export to CAD and CFD tools, 3-D stress, and vibration analysis.

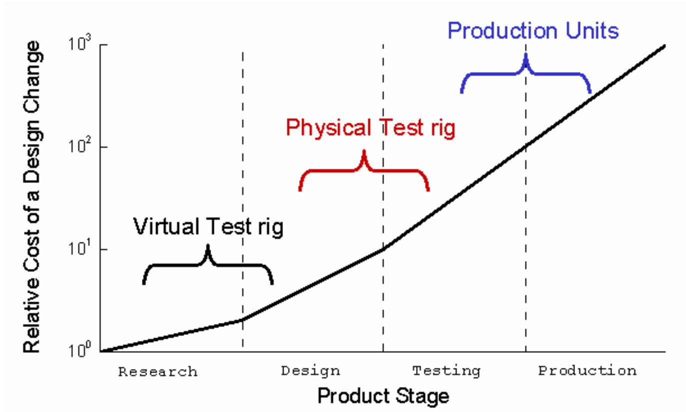

Figure 1. Design Change Cost Impact [1].

Component stress, rotor dynamics, material properties, manufacturing considerations, maintenance, cost, and other factors all impact a final geometry selection and compete with aerodynamic optimization. Rigorous accounting for these disciplines in the design process constitutes multi-disciplinary optimization (MDO). Flexible integration where design module additions are easily possible is a key feature in the creation of such a design system and is a strong point of the proposed system.

In practice, it is often not practical or efficient to fit all these functions within a single software package, thereby reinforcing the need for flexible integration of separate stand-alone modules. Lyons [5] showed the growing importance for a major OEM to integrate different software, including CAD tools, versus expanding capabilities of a single software program to satisfy the needs of engineers. Carty [6] demonstrated how commercial off-the-shelf tools allow for the integration of analysis codes and applications in a modular format, providing an efficient user environment for performing analyses. The application of rapid conceptual design by complete integration of multi-disciplinary design and optimization has enabled the identification of optimal solutions to multiple design disciplines that are often counter intuitive.

The proposed design system solves many of the shortfalls and problems of older design systems. A commercially available director program is used to link together the multiple programs and files of the design system, providing flexible system architecture. In this manner, any software program can be readily incorporated into the design system, either commercial or custom-made, allowing the possibility for future evolution to a full MDO design process. The use of an integration tool allows for a more effective design system. This is achieved in part by decreasing the amount of manual interaction between software modules, thus reducing engineering time and probability of errors. Likewise, having an integrated design process facilitates manipulation and monitoring of the geometry and attendant performance implications.

The principal features of the proposed system are a 1-D code for aerodynamic performance, a master spreadsheet used for central data storage, and a stage solid model. The solid model consists of detailed solid stage part models and flow path volumes for CFD analysis. This is an advantage over other systems in that a detailed stage layout is produced instead of only flow path geometry or non-physical part models.

The reported work represents an example of an undergraduate cooperative project. The relationship between colleges and sponsor companies can be important to the health and growth of both students and company alike. The opportunity for undergraduate students to experience work in their major is of immense value. Instead of waiting until after graduation, the student is able to gain unique work experience in his or her chosen field. The sponsor company benefits from using students to complete projects that do not require significant experience or expertise. Candidate projects might also include using student interns for testing of systems or development of system manuals. In addition, because student interns often lack traditional company experience, their testing of unknown solutions can facilitate the discovery of innovative alternative designs.

DESIGN SYSTEM OVERVIEW

The design process for turbomachinery may incorporate many different software programs and intermediate files. An ideal vision for a fully functioning, mature aerodynamic design system of a centrifugal compressor stage is depicted in Figure 2.

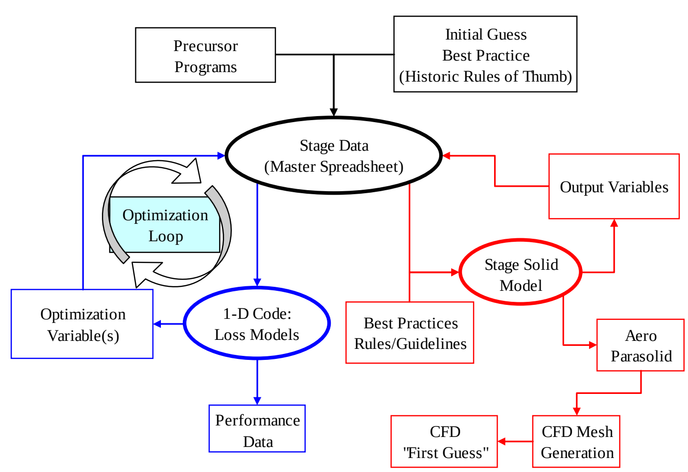

Figure 2: Idealized Design System.

The key features of such a system are a single central data repository and the automatic passing of consistent data between the design modules. The single central data repository (CDR) houses all of the pertinent stage data. At the beginning of the design phase, this data is obtained from best practices and precursor design programs. Once the data is entered into the CDR, the integration model is executed producing performance data and a solid model of the stage. Based on this first iteration, alteration of the stage data commenced. As seen in Figure 2, the stage solid model and the 1-D code modules are integrally linked to the stage data module. Therefore, changes made to the stage data in the CDR automatically update the stage solid model and the inputs for the 1-D code.

All output information including analysis results, component solid models, and 3-D flow path solids are inherently synchronized and up-to-date with the CDR data. In addition, a 3-D geometric model is automatically ready for CFD analysis after each design iteration is completed.

The ideal aerodynamic design system depicted in Figure 2 can utilize the optimization features contained within the director program. Although these features can be used on virtually any parameter of the system, to date it has only been used for fixed-point optimization within the 1-D code.

The current state of the design system developed under this project is shown in Figure 3. It is a subset of the idealized vision and includes the major components of the complete system of Figure 2: CDR, stage solid model, and 1-D code. However, the inter-module linking is currently not fully automated and therefore requires some manual data transfer between modules, represented by dashed lines.

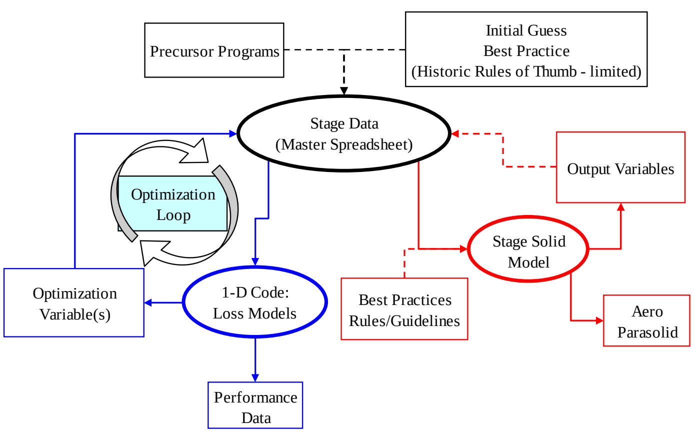

Figure 3. Current Design System.

Within the scope of the current project, the design process focuses solely on the aerodynamics of the stage; however, other aspects could likewise be incorporated into the system. In essence, there would be multiple analysis modules added that would encompass other design considerations such as component stress, rotordynamics, and thermal effects. Stage optimization could then be a true MDO design process.

MODEL COMPONENTS

Master Spreadsheet

The backbone of the design system is the CDR. In the current implementation, this function is accomplished through a master spreadsheet. Reasons for choosing Microsoft Excel for this task include Excel being a universal, engineering "language" and thus the training required for its use is minimal. Additionally, information in Excel is stored in explicitly defined spatial objects, or cells, which made linking to the director program easy and robust. Furthermore, Excel combines both graphical user interface (GUI) and data storage in one file thereby reducing required programming.

The data stored within the master spreadsheet includes basic geometric information of the stage, gas properties, and additional parameters needed to create solid models or tuning and option selected parameters for the 1-D code. The spreadsheet is organized for easy access to a separate stage component, including inlet, impeller, diffuser, return bend, return channel, and volute.

1-D Code

The current design system is linked to a proprietary 1-D performance prediction and stage design code created by the OEM [3]. In the context of the design system, the 1-D tool can be viewed as a transfer function from a set of geometric and operating parameters to performance characteristics, such as stage efficiency. In addition to built-in loss and blade slip models, the code uses a tuning system based on test experiences of the OEM.

LINK TO CAD AND GENERATION OF SOLID MODEL

A stage solid model is also linked to the present design system. As a variable within the CDR is altered, the updated value is passed to the solid model through the director program. The effects of which then automatically propagate through the model due to inherent associativity.

The stage solid model was constructed on a commercially available CAD platform. Figure 4 is an example of the impeller defining sub-model within the solid model.

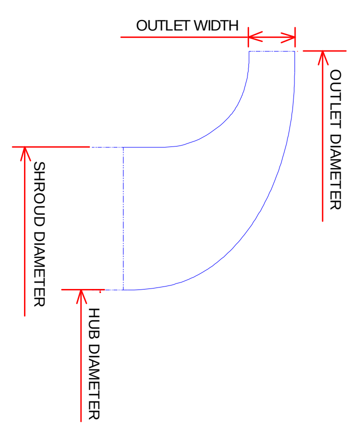

Figure 4. Solid Model Simple Impeller Sketch.

The physical part solids for manufacturing shown in Figure 5 and flow path volumes for 3-D analysis shown in Figure 6 are then developed from these parametric sub-models.

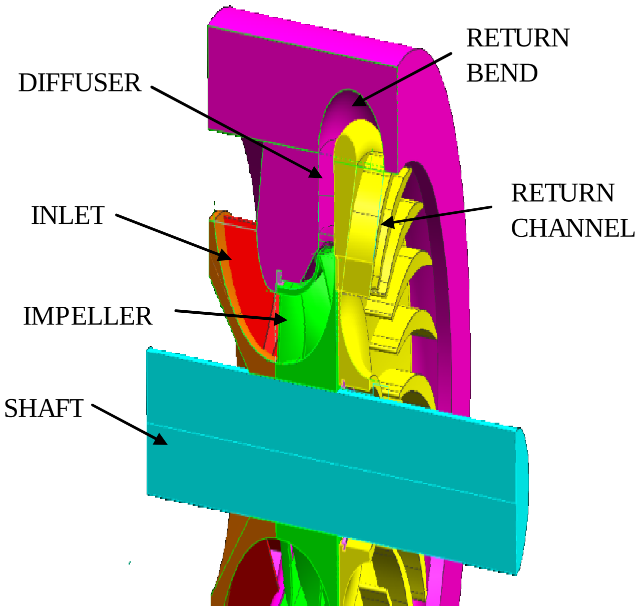

Figure 5. Physical Stage Components.

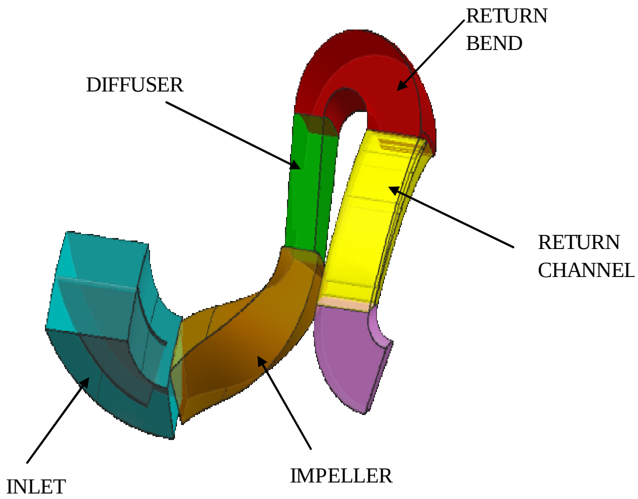

Figure 6. Aero Flow Path Volumes.

OPTIMIZATION STUDY

The optimization features of the director program were used to optimize stage geometry based on performance models of the 1-D Code. Optimization was achieved through the alteration of design parameters until an optimum value of the objective function was obtained without violation of the constraint variable. For example, in an impeller optimization, the exit width and blade angle could be considered the design variables. These variables would then be altered until the best value of the optimization variable, such as stage efficiency, is reached. The discharge pressure level produced by the stage could be considered a constraint variable.

Optimization in the current design system can be performed using three methods available within the director program software: gradient, genetic, or combination [7].

The gradient optimizer is a simple local gradient or slope technique. The process begins at a point, whether random or user specified, and calculates the local slope of the objective and constraint functions. Based on the slope values, a favorable search direction is obtained. This process is then repeated until an optimum value of the objective function is reached. One consequence of using this method is the possibility that it will converge prematurely on a local optimum instead of a global one.

The genetic optimizer mimics the process of natural selection in that it works with several designs, or populations, simultaneously. During each iteration, the objective and constraint functions are analyzed resulting in the birth of new populations by combining the best designs. In this manner, each population progresses towards an optimal solution. An advantage of using this method is that at its conclusion, an array of best design options is available instead of only one. A disadvantage, however, is that more iterations and therefore more time is required to complete this optimization than the other two methods.

The final optimization option is a combination of the two other methods. Like the genetic optimizer, it starts at multiple locations in the design space, evaluating the objective and constraint functions and storing data. Then, rough mathematical models of each function are created. The rest of the process is similar to the gradient optimizer acting at each point, but is more efficient in that the mathematical models better guide the search direction of each point. Therefore, an optimal solution can be reached with less iteration than that of the genetic optimizer.

The optimization features within the director program produce many useful and convenient visualization graphs. This information is important because more than one value or a range of values of a design variable could contribute to the best solutions. An example of such a scenario is shown in Figure 7 with a contour plot of an impeller optimization.

A set of test optimization cases was carried out as part of the development of the design system, ranging from single parameter to multi-parameter optimizations. The boundary constraints for the design parameters were user-defined. Designer's experience and semi-empirical criteria are used in establishing constraints to ensure that the bounds of the mean-line models are not exceeded during the optimization process.

A single parameter optimization was completed for impeller efficiency, the results of which are shown in Figure 8. The impeller tip width was altered and the corresponding change in efficiency was documented.

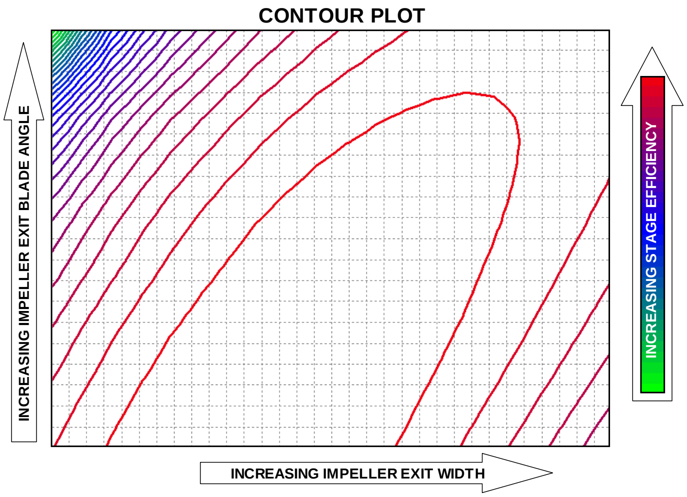

Figure 7. Optimization Results Contour Plot.

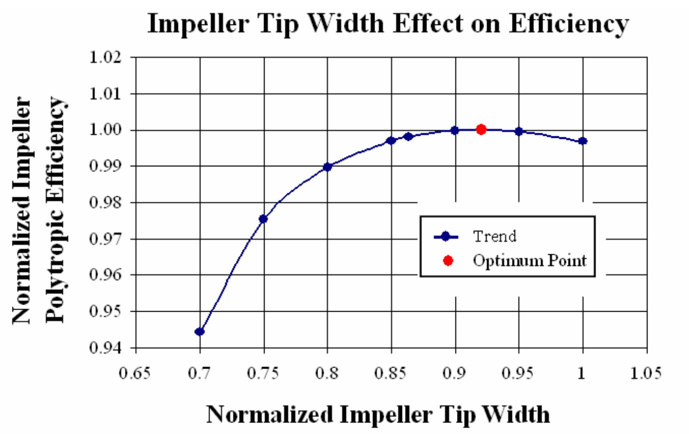

Figure 8. Impeller Width Optimization Results Plot.

A multi-variable optimization was completed on the impeller and the diffuser sections simultaneously. The optimizer within the director program software changed the impeller exit width, the impeller exit blade angle, the diffuser width, and the diffuser exit diameter in order to achieve maximum stage efficiency within a pre-described pressure ratio range. The optimization process was tracked in real time by monitoring the convergence of the objective function and the design parameters by satisfying maximum efficiency goals. Figure 9 displays the progression of the stage efficiency with each generation. The genetic method of optimization was used in this example.

As part of the genetic optimization tool, the software automatically tabulated iteration results as well as highlighted the best designs. Table 1 details the results of twelve iterations along the optimization process. It can be seen that as the iterations progress, the efficiency improves and the constraint range is fulfilled. The resulting solutions are tabulated in Table 2, with the final choice of "best" design being left to the judgement of the user. In both of the tables, the value of each design variables represents a percent increase or decrease from the original starting value.

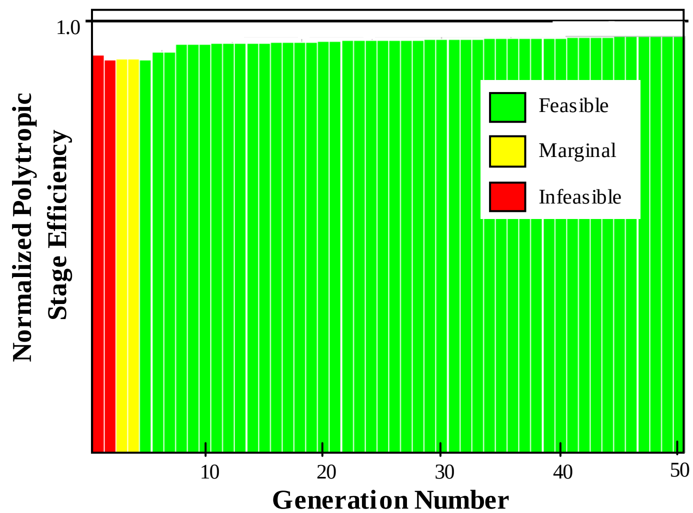

Figure 9. Optimization Progress with Normalized Stage Polytropic Efficiency as Objective Function.

Table 1. Sample Iterations.

	OBJECTIVE	DESIGN VARIABLES				CONSTRAINT	
Iteration #	Normalized Stage Polytropic Efficiency	Impeller Exit Width Trend (%)	Impeller Backsweep Trend (%)	Diffuser Pinch Trend (%)	Diffuser Exit Diameter Trend (%)	Normalized Stage Polytropic Head	Within Range
1	0.89	-7.7	-11.3	-27.6	36.0	0.82	N
50	0.93	-9.9	-15.3	-24.4	1.2	0.87	N
100	0.89	18.5	-0.2	-18.7	21.8	0.77	N
150	0.93	-24.7	-23.4	-2.5	-25.9	0.86	N
200	0.88	-8.7	-50.2	1.7	44.4	0.97	N
300	0.90	-13.3	-45.6	6.2	26.5	0.98	N
400	0.93	45.6	-45.8	-21.7	16.3	1.00	Y
500	0.94	-18.0	-40.3	-8.0	-6.9	0.99	Y
1000	0.95	-17.8	-38.4	8.3	-16.5	0.99	Y
1500	0.96	-12.7	-36.4	9.0	-15.6	0.99	Y
2000	0.96	-8.1	-31.8	6.9	-20.2	0.98	Y
2201	0.96	-3.3	-32.2	0.2	-24.1	0.99	Y

Table 2. Resulting Designs.

	OBJECTIVE	DESIGN VARIABLES				CONSTRAINT	
Design #	Normalized Stage Polytropic Efficiency	Impeller Exit Width Trend (%)	Impeller Backsweep Trend (%)	Diffuser Pinch Trend (%)	Diffuser Exit Diameter Trend (%)	Normalized Stage Polytropic Head	Within Range
1	0.96	-3.32	-32.21	0.20	-24.1	0.99	Y
2	0.96	-3.28	-32.16	0.80	-23.8	0.99	Y
3	0.96	-3.69	-31.84	4.61	-24.7	0.99	Y
4	0.96	-2.69	-32.88	-0.72	-23.6	0.99	Y
5	0.96	-1.87	-33.48	-0.11	-24.3	0.99	Y
6	0.96	-2.40	-32.64	-0.66	-22.5	0.99	Y
7	0.96	-3.11	-32.98	-0.49	-23.0	0.99	Y
8	0.96	-5.10	-32.44	4.55	-25.2	0.99	Y
9	0.96	-4.77	-31.32	7.27	-24.7	0.98	Y
10	0.96	-4.89	-31.89	2.68	-23.1	0.99	Y

Figures depicting the alteration of each design variable and the consequent response of the objective and constraint variables were likewise automatically constructed. The response of the objective function (Figure 10) was re-plotted to include only those iterations that did not violate the constraint function and is shown in Figure 11.

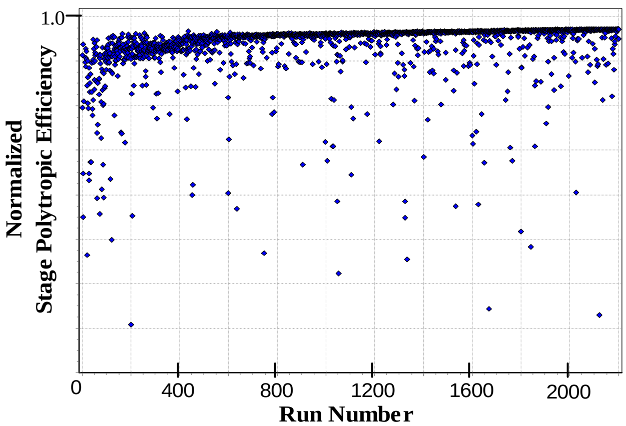

Figure 10. Optimization History with Stage Polytropic Efficiency as Objective Function.

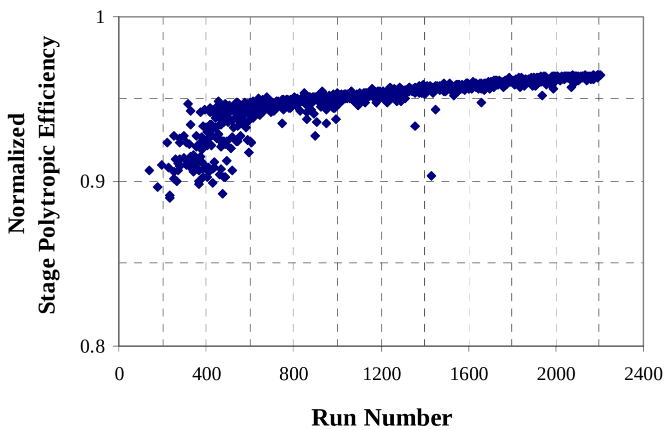

Figure 11. Reformatted Optimization History with Stage Polytropic Efficiency as Objective Function.

In addition to the optimization capabilities of the director program, other features are available that allow for the exploration of the design space. Such features include carpet plots, design of experiments (DOEs), and parametric studies. The carpet plot tool, in essence, "maps" the response of altering a design parameter within defined boundaries. Figure 12 illustrates an example of a carpet plot. Impeller exit width and blade angle were used as design parameters in this analytical study, with the stage polytropic efficiency as the response variable. As can be seen in the figure, there are different combinations of exit width and angle that lend to high efficiency values.

As can be seen in the above examples, practical performance improvements were achieved through the use of the optimization portion of the design system. It is important to note that optimization can be useful for many aspects of the design, not just aerodynamic design. Therefore, this optimization portion is of extreme value in and of itself.

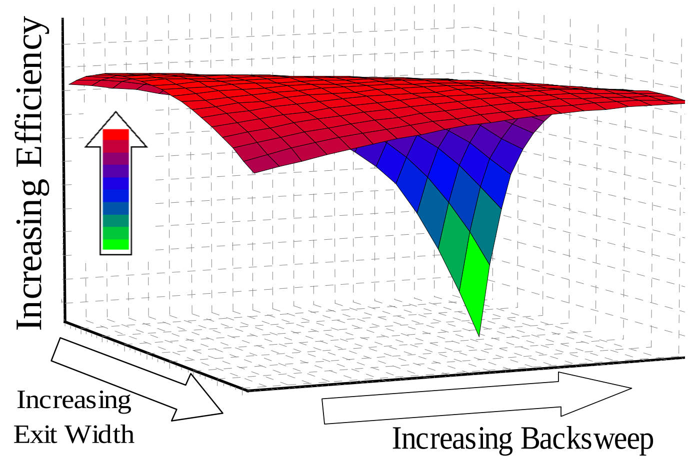

Figure 12. Impeller Optimization Carpet Plot.

The optimized solution based on mean-line modeling can be validated by high fidelity 3-D CFD analysis and, ultimately, by test. Such important validation, as well as assessment of accuracy of 1-D prediction, lies beyond the scope of the undergraduate cooperative study program and could be the subject of a different project.

TECHNICAL SUMMARY

The developed system integrates mean-line aerodynamic design and analysis tools with spatial CAD geometry generation and optimization. It offers a variety of benefits when compared with the traditional design process in the turbomachinery industry.

The design system relies on commercially available integration and optimization software, which allows significant reduction of engineering time and related cost that would otherwise be spent on extensive custom programming.

Because the programs used for design are integrally linked, there are no data transfer errors.

It is sometimes important to document individual design iterations. The CDR is a snapshot of the design, thereby allowing the possibility for self-documentation of design iterations.

The system is flexible providing a modular "plug and play" architecture that allows easy modification, extension, and improvement.

The optimization loop of the design system is flexible and versatile. Any 1-D parameter or combination could be a design variable(s), the objective function can be customized to fit the desired purpose, and realistic constraints are built into the director program software.

The proposed design system is capable of generating a preliminary 3-D, mesh-ready geometry based on 1-D input. This lends to a shorter time needed per design iteration and a "watertight" geometry that can be automatically created for use in CFD meshing.

The original work scope did not include an explicitly defined impeller blade. However, later in the project this was revised and a preliminary impeller blade definition was added to the solid model. Also added during this revision period were enhancements to the diffuser section.

A follow-on project over the next internship period is planned to focus on further automation of optimization processes and allow for creation of both standard and custom-designed compressor stage geometries. These geometries could be considered a “pre-screened” input for high fidelity 3-D CFD studies.

EDUCATIONAL ASPECTS

Work-study programs like cooperative education are beneficial to both the student and the sponsor company. Students are able to gain unique industrial experience in their chosen field prior to graduation. The sponsor company has an excellent opportunity to screen potential candidates and supplement their existing engineering work force with intern work.

The undergraduate student assigned to this project is a senior pursuing a Bachelor’s of Science degree in mechanical engineering. Prior to this project, the student completed several internships at the same OEM, which resulted in enhanced CAD skills, the ability to perform mechanical analyses, and some familiarization with turbomachinery design rules and procedures. These experiences materially assisted in the development of the design system outlined in this paper.

As this project was a real, funded, project by the OEM, an introduction to project management was achieved. Work progress was monitored on weekly basis and results were presented to the engineering team.

During the course of this project, the student intern was exposed to significant educational opportunities. The creation of the design system resulted in introductory exposure to aerodynamic design and analysis. Likewise, working with a team of experienced engineers provided a wealth of knowledge in many aspects of industry, manufacturing, and engineering in general. Familiarization with industry standards, internal specifications, and best practices were identified as potentials for improvement, for which learning material and consultations were provided.

As a result of working on the 1-D code itself, improved programming skills and an introduction to the code structure and tuning functions were achieved.

The exposure to state-of-the-art modeling and drafting packages was a unique opportunity that would have been difficult to achieve in a college environment.

In the process of creating and troubleshooting the optimization portion of the design system, valuable insight into the optimization process was provided. Through simple one-parameter manual optimizations using the 1-D code, exposure to aerodynamic design and compressor trends was gained. As optimization is common in many facets of engineering, this exposure will be a benefit in future practical work situations.

The integration portion of the project illuminated a new direction in the development of computational based design systems. In this new type of approach, the engineer can readily create complex customized program systems. It was an excellent opportunity to be exposed to such cutting-edge software.

Finally, the experience of writing and presenting this paper to the engineering community has been a challenging but rewarding experience giving valuable insight into the field of technical communication.

ACKNOWLEDGMENTS

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