1994

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DESIGN OF COMPRESSOR VALVE SYSTEM UTILIZING AN EXPERT SYSTEM

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ABSTRACT
An expert system to design compressor valve systems has been developed. Design process is viewed as a chain of decisions based on the results of necessary analyses. Actual design is implemented by the interaction between the expert system and the user. In this work, it is demonstrated how a final design is achieved by utilizing the rule bases and analysis capability of the system. The structure of the rule bases and related parameter studies are also explained. Advantages of using an expert system approach for valve designs are explained using a practical example.

INTRODUCTION
Design of the valve system is the most important part in the compressor design. To develop a reliable and efficient valve design procedure, one has to consider the performance requirements as well as the reliability requirements [1, 2, 4]. An expert system technique [6, 7] can be used to deal with the complexity and iterative nature of the mechanical design if it is applied to a narrowly defined particular application [3, 12, 13]. An expert system can be made by using a clever mixture of the analysis/simulation and decision making processes to emulate the design procedure [5, 8, 9, 10, 11].

In this work, an expert system has been developed so that it serves as a useful assistant for compressor valve designers. Its objective is to help the designer to interpret the performance of the current design status, and to provide the knowledge for necessary decisions at each critical point. The system has been developed using EXSYS, an expert system shell, to take advantages of some built-in features. General information used by the rule base of the system is provided from analysis programs integrated with the system. The analysis results are interpreted and compared with design guide lines and suggestions to improve the design are made by the rule base. Performances of an intermediate or the final design can also be checked by the P-V diagram simulation program.

Possible advantages of using the expert system developed are summarized as: 1) It provides analytical tools and guiding functions. 2) It makes efficient and exhaustive design iterations possible, and 3) It makes the design procedure more uniform and consistent.

DESIGN PROCEDURE
As the first step to computerize any design procedure, one can consider a typical procedure employed by a human designer. The steps identified in the procedure can be divided into several different categories such as analyses, interpretations, diagnoses and decisions.

A typical procedure of the valve design seems to be composed of the following steps:
1) Rough sizing of the valve ports based on an idealized P-V diagram.
2) Decide an initial design of the valve reed. Existing designs may be used instead of the steps 1) and 2).
3) Analyze the performance of the design in terms of the efficiency and reliability.
4) Evaluate the current design based on the result from 3).
5) Accept the design if it is satisfactory, or improve it to eliminate the problems diagnosed in step 4).

In the system developed in this work, steps 1), 2) and 3) are done by using the valve analysis program while the steps 4) and 5) are done by using the expert rule base. In this report, the expert system parts (steps 4) and 5)) are reported in detail.

Five design criteria for the valve design used in this work are:

\[ \sigma_{\text{inf}} < \sigma_{\text{inf,allowable}} \] (1)
\[ \sigma_b < \sigma_{b, \text{allowable}} \]  
(2)

\[ M < M_{\text{recommended}} \]  
(3)

\[ t_c < t_{c, \text{recommended}} \]  
(4)

\[ v_{\text{imp}} < v_{\text{imp, recommended}} \]  
(5)

where, \( \sigma_{\text{inf}} \) indicates the bending stress when the valve is pushed into the port, \( \sigma_b \) is the bending stress when the valve is fully open, \( M \) is the Mach number of the valve flow, \( t_c \) is the valve closing time, and \( v_{\text{imp}} \) is the valve impact velocity. Details of the calculation procedure for these parameters are found in reference [3]. In the system, the five performance variables are normalized, therefore the value 1 or less means an acceptable design.

OVERVIEW OF THE EXPERT SYSTEM

In this work, the scope of the expert system is limited to the compressor valve design to make the necessary knowledge base workable size. Any other functions are made as separate programs and combined with the system [12, 13]. Compressor performance simulation program, graphics routines and gas manifold analysis/design programs work in parallel with the valve design system.

The decisions made by the designer in a typical design process are usually based on different kinds of information. Some of them are made based on the analysis results, while others have to be made based on his experience and heuristics. In the valve design, it is intended to use as much analytical information as possible. Suggestions for design improvement are made utilizing the knowledge on the relationship between the design variables and performance criteria.

The basic structure of a typical expert system is shown in Figure 1. As seen in figure, the expert system consists of four components: input/output facility, knowledge acquisition, knowledge base and inference engine [6, 7]. The input/output facility handles the user input, oversees the system behavior and decision process of the system during the design. It also reports the intermediate results and the final conclusions for the user, answers questions about how a particular conclusion was reached. The output is made in a form of the report file which contains the diagnoses/suggestions about the selected valve design model.

Knowledge acquisition is a difficult and often controversial phase in the development of the expert system. In this work, necessary information is fed into the expert system in the form of data file which are extracted from the results of the analysis part.

Knowledge base, also called the rule-base, is for the acquisition and representation of the design knowledge. The knowledge base in the expert system contains facts and rules, where the former is used as the basis for the action contained in the latter. The rules are in a form of IF-THEN statement, i.e.,

IF "premise", THEN "conclusion".

The premise or IF part of the rule may consist of many conditions and the conclusion or THEN part of the rule may have several actions. The rule interpreter compares the IF part of the rule to the available facts which are given to the system or obtained by the actions in other THEN parts. On obtaining a match, the system executes the conclusion in THEN part. For example, if Mach number is calculated higher than the recommended value in the design considered, the following rule is fired.

Rule 1: IF \( |M| > 1 \)  
THEN Mach number is high

Therefore, all the rules which have IF "Mach number is high" as the premise are fired subsequently. For example, the following rule will be fired.

Rule 2: IF Mach number is high  
THEN Effective flow area is too low

Execution of the THEN part in Rule 2 makes chain reactions. For example, if the Rules 3 and 4 are,

Rule 3: IF Effective flow area is too low  
AND \( |A_f| < |A_{f, \text{req}}| \)  
THEN Exit area due to valve deflection is too low

Rule 4: IF Exit area due to valve deflection is too low  
THEN Reduce valve width  
AND Reduce valve thickness  
AND Increase valve length

Now, the system concludes that the Mach number is high because the valve deflection is too small and issues corresponding remedies. Similarly, all possible conclusions are reached by chain actions from several hundred rules of the system. The search procedure to reach the conclusions is so called inference engine part. In this work, the forward chaining strategy is used as the inference engine. The principle on how the inference engine works can be found in [6].

SENSITIVITY ANALYSIS
Design rules can be made based on the relationship between the design variables and the performance variables. Extensive analysis work has been done on the sensitivity of the aforementioned five performance variables to design variables. The design variables of interest are taken as the valve port size, valve length, valve width, and valve thickness. The results of the sensitivity analysis are shown in Tables 1 and 2, where Table 1 is for the both end simply-supported type valve and Table 2 is for the cantilever type valve.

The sensitivity relation is completely different depending on whether the valve stopper is active or not. Here, active means that the valve touches the stopper when it is fully deflected. Especially, the bending stress and the impact velocity have opposite relations to the valve thickness (t) depending on whether the valve is active or not. As the valve length increases, the bending stress can be either increased or reduced if the stopper is inactive, while it is always reduced for the active case. Other design criteria is not influenced by the thickness changes if the stopper is active.

Therefore, in order to apply the expert system design concept to the compressor valve design, the effects of the valve stopper should be considered. Figure 2 shows that how the valve stopper affects the behavior of design variables. The case with the valve stopper is further classified into 8 cases and the case without valve stopper is further classified into 3 cases as shown.

The system first checks the existence of the valve stopper to decide which kind of rules are to be used. If the stopper exists, its height is checked to see if it is proper. If there is no stopper, then the valve deflection is checked if it deflects unnecessarily too much. Then, the system finds a reasonable valve deflection which provides an appropriate flow area without making too large valve deflection. By comparing the stopper height with this desired deflection, the stopper height is classified into three cases: too high, too low and appropriate as shown in Figure 2.

When a stopper is considered too high and the valve deflection is unnecessarily too large, the following diagnoses are deducted by the rule base.

Stopper exists $\rightarrow$ h > $h_{\text{def (high)}}$ $\rightarrow$ $\delta < h$(not active) $\rightarrow$ $\delta > h_{\text{def}}$

Therefore, the design is diagnosed as: 1) A valve stopper exists, 2) The stopper height is too high, 3) The stopper is not active, i.e., the stopper height is too large compared with the actual valve deflection, and 4) The valve deflection is too large. This part of rule-bases is executed prior to any other design criteria being evaluated. In the next level rules, the rule-based system diagnoses the design based on the five performance criteria and makes necessary prescriptions. In the above case, three prescriptions are made. They are; 1) Reduce the stopper height (h), 2) Reduce the valve deflection ($\delta$), and 3) Increase the valve deflection ($\delta$).

Notice that the last two prescriptions are conflicting. This is because the design space is reduced step by step by eliminating obviously non-feasible conditions. Diagnosis and suggestion parts are composed of approximately 660 rules based on the parameter relationships between the performance variables and the design variables.

The system also provides numerical values of the sensitivities of the design parameters in addition to the rule base recommendations. The changes of the five performance variables with respect to the 10% change of the design variables are calculated and displayed in the suggestion part of the expert design system. By referring to these results, a designer can estimate how much the design variable should be changed to satisfy the design requirement for the selected model.

**EXAMPLE**

In this section, an example to design the valve system of a reciprocating piston type compressor is shown. It is assumed that the valve system has a circular port and a uniform width reed. The port and reed dimensions of the discharge side are: port diameter (D) is 0.26 cm, valve length (L) is 1.57 cm, valve length (Lp) is 1.07 cm, valve width (W) is 1.3 cm, and valve thickness (t) is 0.015 cm. Utilizing the analysis part of the system using these initial design variables, the performance of the current design is obtained first as shown in Table 3. Notice that any value greater than 1 indicates the corresponding criterion is violated.

In the table, the pair (2,2) is the initial design of port/valve. The analysis result using the initial design is evaluated in the expert design system which creates a report file (Figure 3). This file contains diagnosis of existing problems and necessary suggestions for the new design. The report is made in two levels. The first level report has suggestions to improve each violated design criterion without considering its effect to the other criteria. Therefore, this often produces some conflicting suggestions. In the second and higher level report, the conflicting suggestions are excluded. In this case, there are two violated design criteria, the Mach number and
the valve closing time. The valve length (L) for the valve closing time and the port size (D) for Mach number are changed (Figure 3) since they are the most sensitive parameters to the violated design criteria. As the result, a new design (4,4) is created whose performance is shown in Table 3. Although there are still two violated design criteria, Mach number is reduced from 2.1 to 1.02. Which is adopted as the final design without more iterations in this example. In practice, the iteration can be continued until the designer is satisfied with the results.

CONCLUDING REMARKS

An expert system to analyze and design the compressor valve system has been developed. Five design criteria are used to evaluate the performance and reliability of the compressor. Parameter study including the effect of the valve stopper has been done to build the design rule part. The expert system part is composed of the diagnosis part and the suggestion part. The diagnosis part identifies the causes of the design problems in the valve system and the suggestion part provides necessary recommendations to solve them. Sensitivities of the parameters are also provided to reduce the number of iterations of the design process. It is believed that the system will help the user to obtain better valve designs in shorter time if it is properly used.

ACKNOWLEDGMENT

The authors would like to thank research consortium, Daewoo Electronics, Daikin Industries, Goldstar Electronics and Samsung Electronics for their support.

REFERENCES

2. W. Soedel, "Introduction to Computer Simulation of Positive Displacement Type Compressor," Short Course Note, Purdue University, West Lafayette, IN, 1972.
Table 1 Sensitivity (Both end simply supported type valve)

* Change of the performance parameters according to the positive change of the design variables

<table>
<thead>
<tr>
<th>Inactive case</th>
<th>( \delta )</th>
<th>( t_c )</th>
<th>M</th>
<th>( \sigma_{inf} )</th>
<th>( \sigma_b )</th>
<th>( \nu_{imp} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>R</td>
<td>X</td>
<td>R</td>
<td>I</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>L</td>
<td>I</td>
<td>I</td>
<td>R</td>
<td>X</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>W</td>
<td>R</td>
<td>X</td>
<td>I</td>
<td>X</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>t</td>
<td>R</td>
<td>R</td>
<td>I</td>
<td>R</td>
<td>R</td>
<td>R</td>
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</tbody>
</table>

Active case

<table>
<thead>
<tr>
<th>( \delta )</th>
<th>( t_c )</th>
<th>M</th>
<th>( \sigma_{inf} )</th>
<th>( \sigma_b )</th>
<th>( \nu_{imp} )</th>
</tr>
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<tbody>
<tr>
<td>D</td>
<td>R</td>
<td>X</td>
<td>R</td>
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<td>X</td>
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<td>L</td>
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<td>I</td>
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<tr>
<td>W</td>
<td>R</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>t</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>I</td>
<td>I</td>
</tr>
</tbody>
</table>

D, L, W, t are port diameter, valve length, width, thickness and \( h \) is stopper height
Lp is valve length up to flow force
R: reduced, I: increased, X: no change

Table 2 Sensitivity (Cantilever type valve)

<table>
<thead>
<tr>
<th>Inactive case</th>
<th>( \delta )</th>
<th>( t_c )</th>
<th>M</th>
<th>( \sigma_{inf} )</th>
<th>( \sigma_b )</th>
<th>( \nu_{imp} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>R</td>
<td>X</td>
<td>R</td>
<td>I</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>L</td>
<td>X</td>
<td>I</td>
<td>X</td>
<td>X</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>W</td>
<td>R</td>
<td>X</td>
<td>I</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>Lp</td>
<td>I</td>
<td>X</td>
<td>R</td>
<td>I</td>
<td>R</td>
<td>I</td>
</tr>
</tbody>
</table>

Active case

<table>
<thead>
<tr>
<th>( \delta )</th>
<th>( t_c )</th>
<th>M</th>
<th>( \sigma_{inf} )</th>
<th>( \sigma_b )</th>
<th>( \nu_{imp} )</th>
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<tbody>
<tr>
<td>D</td>
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<td>R</td>
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<tr>
<td>t</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>I</td>
<td>I</td>
</tr>
</tbody>
</table>

Table 3 Analysis results of the discharge side

<table>
<thead>
<tr>
<th>Design</th>
<th>Stop</th>
<th>M</th>
<th>( t_c )</th>
<th>( \sigma_{inf} )</th>
<th>( \sigma_b )</th>
<th>( \nu_{imp} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2.2)</td>
<td>1.00</td>
<td>2.10</td>
<td>2.95</td>
<td>0.16</td>
<td>0.90</td>
<td>0.62</td>
</tr>
<tr>
<td>(4.4)</td>
<td>0.85</td>
<td>1.02</td>
<td>2.65</td>
<td>0.42</td>
<td>0.86</td>
<td>0.59</td>
</tr>
</tbody>
</table>

\( \ast \) is (port, valve)

Knowledge Base

![Fig. 1 Architecture of an Expert System](image)

Stopper

![Fig. 2 Diagram of the effects of Stopper height](image)

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REPORT OF THE ANALYSIS RESULT USING EXPERT SYSTEM

RECOUERATING PISTON TYPE COMPRESSOR (CONNECTING ROD TYPE)

* The Selected Port/Valve System of the Compressor is:
  THE PORT/VALVE PAIR (2,2) IS ON THE DISCHARGE SIDE

** THIS IS THE FIRST LEVEL REPORT **

* Valve Closing Time (Tc)
  1) Diagnoses:
     * Valve closing time is too high
       (1) Natural frequency (Wn) is too low
  2) Suggestions:
     To improve (1), increase natural frequency (Wn)
     To do that,
       i) Reduce valve stopper height (H)
       ii) Reduce valve length (L)
           If valve length (L) is reduced by 10%, then closing time will be reduced by 18.999%
       iii) Increase valve thickness (t)
           If valve thickness (t) is increased by 10%, then closing time will be reduced by 9.09%

* Mach Number (M)
  1) Diagnoses:
     * Mach number is too high
       (1) Flow velocity is too high
           (1.1) Effective flow area is too low
           (1.1.1) Port area (Ao) and Exit area due to valve deflection (A1) are too low
  2) Suggestions:
     * To improve (1.1.1), increase port area (Ao)

**This is the second and higher level report**

* Valve Closing Time and Mach Number
  1) Diagnoses:
     * Valve closing time is too high & Mach number is too high
     i.e., Valve closing time is too high & Port area (Ao) and Exit area (A1) are too low
  2) Suggestions:
     i) Reduce valve length (L) (Cantilever)
     * If valve length (L) is reduced by 10%, then closing time will be reduced by 18.999%
     ii) Increase port size (D)
     * If port size (D) is increased by 10%, then Mach number will be reduced by 15.41%
     iii) Increase number of port

** END OF DIAGNOSES AND SUGGESTIONS **

Fig. 3 Report file of discharge side (Reciprocating Piston)