1990

Development of an Expert System for Compressor Valve Design

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DEVELOPMENT OF AN EXPERT SYSTEM
FOR COMPRESSOR VALVE DESIGN

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ABSTRACT

An expert system is developed for compressor valve designs. The system, comprised of two parts, evaluates existing designs and recommends directions for design improvement. The design analysis and evaluation part rates valve designs based on important design criteria for compressor performance and reliability. A uniquely structured data base and design rules extracted from parameter study are used in the design improvement part. The effectiveness of the system in a real design situation is demonstrated by an example.

INTRODUCTION

Because of the artistic nature of the design process, engineers often find it difficult to apply computer design programs to actual product design. For example, design objectives and constraints can seldom be expressed exactly in mathematical forms. There are many occasions when designers should rely on their intuition and experience to make a decision rather than numerical calculations. Expert systems, a special branch of artificial intelligence, are considered a promising concept to overcome such difficulties by utilizing the logical processing power of computers to support designers. Some application examples in the mechanical design area can be found in references [1,2,3].

The expert system developed in this work is intended to be a useful assistant for compressor valve designers. The program is composed of two parts, which are the analysis/evaluation part and the expert design part. The first part analyzes existing valve designs and ranks them according to various valve design criteria. The second part recommends directions for better designs and helps the user to accumulate knowledge on valve design.

ANALYSIS OF VALVE DESIGNS

The analysis part evaluates existing valve designs and provides basic information for the design improvement part. The analysis part was made computationally efficient so that the evaluation and design part can be made simple and straightforward. Reference[4] can be used for detailed discussion on the theory and procedure used in this work. Refer to illustrations in Figures 1 and 2 for the definition of variables.

(1) Calculation of Valve Flow and Deflection

If a constant motor speed, ideal compressor cycle with polytropic process are assumed,

$$\theta(t) = \omega t \qquad (1)$$

$$V(t) = V(\theta) \qquad (2)$$

$$P = P_o \left(\frac{V_o}{V(t)} \right)^n \qquad (3)$$

where, θ and ω are the angular displacement and speed of motor, t is time, P,V are the cylinder pressure and volume and subscript o denotes reference values. From the P-V diagram in Figure 1, $\theta_1 = 0^o$ and $\theta_3 = 180^o$. θ_2 and θ_4 can be found by trial and error utilizing equations (1),(2) and (3). Then the flow rates through the valves are;

$$Q_s = \frac{\omega (V_1 - V_4)}{360^o - (\theta_4 - \theta_1)} \qquad (4)$$

$$Q_d = \frac{\omega (V_3 - V_2)}{\theta_3 - \theta_2} \quad (5)$$

Flow speed in terms of Mach number M is given by;

$$M = \frac{Q}{A_{eff} \cdot C} \quad (6)$$

where C is the speed of sound and A_{eff} the effective flow area given by equation (7) from reference[5].

$$A_{eff} = \frac{K_o A_o}{\sqrt{1 + \left(\frac{A_o}{A_1} \right)^2}} \quad (7)$$

where, K_o is the flow coefficient, A_o is the port area, A_1 is the area formed by the displacement δ and valve seat with perimeter of length L_p.

$$A_1 = L_p \cdot \delta \quad (8)$$

The valve deflection can be calculated if the valve force and equivalent stiffness are known;

$$\delta = \frac{F_{valve}}{K_e} \quad (9)$$

$$F_{valve} = \Delta P \cdot A_F \quad (10)$$

$$\Delta P = \frac{1}{2} \rho_o (M C)^2 \quad (11)$$

where, ρ_o is the density of gas flowing through the valve. The effective area A_F is,

$$A_F = A_d + A_e^2 \left(\frac{1}{A_o} - \frac{A_d - A_p}{A_1^2} \right) \quad (12)$$

See Figure 2 for definitions of A_d and A_p. Instead of equations (7) and (12), any other theoretical or experimental models may be used for A_{eff} and A_F. In general, equations (6) to (12) should be solved iteratively because A_F and A_{eff} are functions of valve displacement δ.

EVALUATION OF VALVE DESIGNS

(1) Design Criteria

Design criteria used in this work are

$\sigma_{inf} < \sigma_{inf,allowable}$ (13) (bending stress when the valve is inflected into the port)

$\sigma_b < \sigma_{b,allowable}$ (14) (bending stress by valve deflection)

$M < M_{recommended}$ (15) (Mach number, flow speed restriction)

$t_c = t_c (\omega_n) < t_{c,\ recommended}$ (16) (Valve closing time)

$V_{imp} = V_{imp} (\omega_n, \delta) < V_{imp,\ max}$ (17) (Impact velocity)

where, ω_n is the first natural frequency of the valve. Valve closing time t_c and impact velocity V_{imp} may be calculated from an equivalent one degree of freedom model of the valve subjected to an initial displacement δ.

Figure 3 shows an evaluation results of 30 different valve designs, which are combinations of 10 different designs of port and 3 different designs of valve reeds. The calculations were made to evaluate valve systems for a fractional horsepower reciprocating air compressor. Scores of all design criteria are nondimensionalized. For example, 0.83 in the Mach number column in Figure 3 means that the design has the flow velocity of 83 % of the recommended Mach number. The column corresponding to "STOP" is the ratio of valve displacement to the valve stopper height. Equations (13) and (14) are reliability conditions and equations (15) to (17) are related to the compressor performance.

(2) Rating Designs

As it is shown in Figure 3, the program checks geometric constraints and performance/reliability criteria. Geometrical constraints are treated as fail/pass criteria (0,1) and are not summed to the total score. Individual scores less than 0.4 are taken as 0.4, to prevent possible misleading interpretations. Otherwise, a design which has a 0.99 point for the bending stress and 0.1 for all others would have a better score than the design which has points between 0.4 and 0.5 for all criteria. In fact, the former design is marginal in bending stress safety and overdesigned in general compared with the latter which has to be regarded as a better design for most applications.

All designs are first sorted according to the number of violations, then according to the total score within the same number of violations. Therefore, the designs with no violation are acceptable designs, and the one with the lowest score among them is considered the best design.

(3) Structure of Data Bases

Figure 4 shows the structure of the data base within this program. The program calculates for all combinations of port designs and reed designs in two different data files. There are some advantages in using different files for valve port and reed data. First, the maintenance of design data is easy because the number of records in the data becomes much smaller. Second, when the user adds a new port design with a matching valve reed in mind, the program automatically checks to determine if there are any better valve reed designs for the port. It is the same when a new valve reed design is added.

Parameters in the data bases were uniquely chosen to minimize the related computations. For example, the bending stress of a unit thickness reed inflected by the unit pressure differential is used in the port data (see σ_{inf}^* in equation 13). Therefore the actual inflected bending stress of any combination of the reed and port is calculated simply by,

$$\sigma_{inf} = \sigma_{inf}^* \cdot t^2 \cdot \Delta P_{max} \qquad (18)$$

where, t is the thickness of the valve reed and ΔP_{max} is the maximum pressure differential. Similarly, the bending stress of the valve reed due to a unit valve force, σ_b^* is used in the data base of valve reed design. For valve ports and reeds of complex geometries, finite element method may be used for the evaluation of bending stresses and natural frequencies.

EXPERT DESIGN PART

(1) Design Rules

The design part was made to assist a valve designer to make decisions when designing new valve systems or improve existing designs. The rule bases are made by studying the effect of important design parameters on compressor performance and reliability. Table 1 shows the result of design parameter study for the most simple valve system with a valve reed of cantilever type and a circular port. Proper interpretation would allow one to extend the result to more general cases. For example, the diameter in Table 1 should be interpreted as an equivalent diameter for a non- circular port.

The design rules are applied to the criterion with the worst score of the designs selected by the user. For example, if the Mach number was the criterion to be improved in the design, the rule to be applied will be;

i. Increase D (if D is the maximum diameter among active ports in port data) where, active ports are the ports which are not violating geometric constraints.

ii. Decrease t (if t is the minimum among the reeds in reed data.)
iii. Reduce the stiffness (if the valve stop is not active.)
iv. Increase the valve stopper height if (the height < 0.2 D .and. the stop is active)

where, active stop in iii. and iv. means that the valve is in contact with the stopper by the static deflection.

Design rules for other criteria were made similarly. When no suggestion is available, the system recommends to increase the number of ports or to relax some of active geometric constraints.

(2) Procedure to Design with the Expert System

The overall design procedure using the system developed in this work is illustrated in Figure 5. The user initiates a new design using a working data base. The working data base can be a part of the master data base downloaded or any initial draft designs. The design is refined as the user iterates the procedure in Figure 5. At the end of the procedure, newly achieved designs may be added to the master design data base so that they can be used as the basis for other designs. Design knowledge is accumulated temporarily in the working data base, and permanently in the master file. In actual applications, one can activate or deactivate some designs if necessary, or log the number of usage of designs to give some favor to more frequently used, better proven designs.

One example taken from actual applications is shown in Figure 6. The case is to design the valve system for a new compressor with twice the flow requirement of the compressor in Figure 3. In the example, the user starts with the port and valve data for the existing smaller compressors and arrives at new designs which satisfy all design criteria. In Figure 7, a performance comparison was made by using computer simulated indicator diagrams of the compressor with one of old valve designs and the compressor with a final valve design.

CONCLUDING REMARKS

This paper has been concerned with an expert system for compressor valve design. The system was made very simple in its logical and analytical structure. It is assumed that decisions are essentially made by the user with the assistant of computational and logical power of the expert system.

Although the program is already practical and effective in actual design applications, improvement can be made in many ways. Obviously, improving the user interface by using graphics and higher level languages like LISP will be desirable. Design trend, which is currently fixed in the program based on parameter study, may be calculated numerically in the program so that not only the directions but also the magnitude of design changes can be suggested. Weight factors may be used for each design criterion to emphasize special requirements for special applications. The most important improvement will be to extend and refine the design rules by utilizing the experience of using the system in actual designs.

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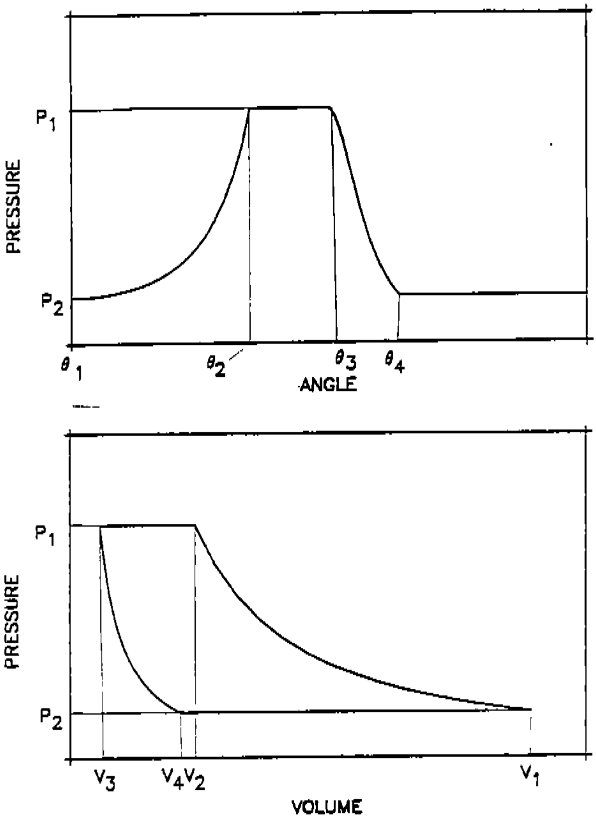


Figure 1 Idealized pressure diagrams for valve opening time determination

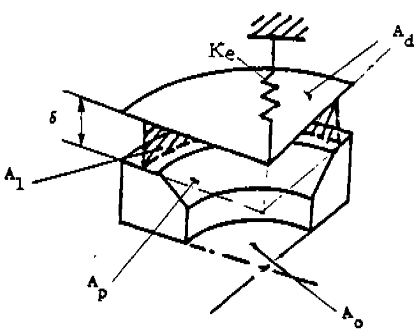


Figure 2 Schema to obtain effective areas

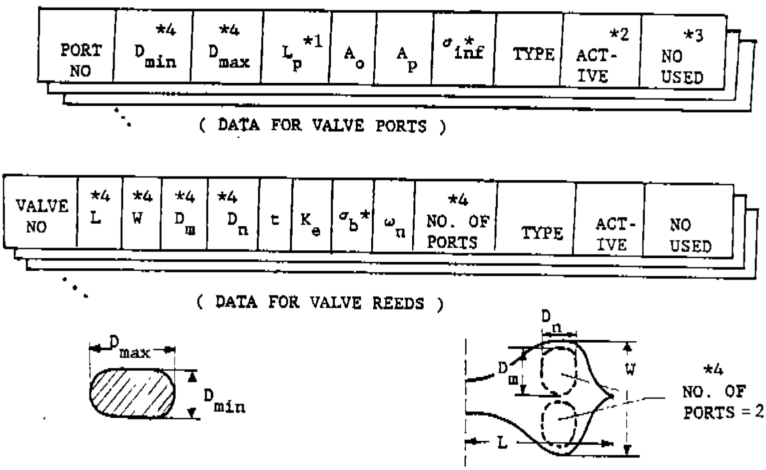
SUCTION VALVE

PORT	VALVE	GEO CONS. L	W	Dm	Dn	INF stress	STOP	MACH NO	BEND. stress	clos. time	IMP. vel.	NO VIOL	SCORE
9	3	0	0	0	0	.47	.17	.79	.34	.32	.31	0	2.46
8	3	0	0	0	0	.42	.19	.85	.36	.32	.34	0	2.48
7	3	0	0	0	0	.37	.20	.94	.39	.32	.36	0	2.44
9	2	0	0	0	0	.73	.29	.71	.45	.40	.42	0	2.71
8	2	0	0	0	0	.66	.32	.78	.50	.40	.46	0	2.79
7	2	0	0	0	0	.58	.35	.87	.55	.40	.51	0	2.92
6	2	0	0	0	0	.51	.40	.98	.62	.40	.57	0	3.09
6	3	0	0	0	0	.33	.22	1.04	.43	.32	.40	1	2.67
5	3	0	0	0	0	.28	.24	1.15	.47	.32	.44	1	2.86
4	3	0	0	0	0	.25	.27	1.31	.53	.32	.49	1	3.13

DISCHARGE VALVE

PORT	VALVE	GEO CONS. L	W	Dm	Dn	INF stress	STOP	MACH NO	BEND. stress	clos. time	IMP. vel.	NO VIOL	SCORE
9	3	0	0	0	0	.47	.26	.54	.50	.65	.23	0	2.56
8	3	0	0	0	0	.42	.28	.59	.55	.65	.25	0	2.61
7	3	0	0	0	0	.37	.31	.65	.60	.65	.28	0	2.71
6	3	0	0	0	0	.33	.35	.73	.68	.65	.31	0	2.87
5	3	0	0	0	0	.28	.39	.83	.76	.65	.35	0	3.04
9	2	0	0	0	0	.73	.46	.50	.72	.82	.33	0	3.17
8	2	0	0	0	0	.66	.51	.56	.80	.82	.36	0	3.23
4	3	0	0	0	0	.25	.44	.95	.86	.65	.39	0	3.26
7	2	0	0	0	0	.58	.58	.63	.90	.82	.41	0	3.34
6	2	0	0	0	0	.51	.66	.71	1.02	.82	.47	1	3.53

Figure 3 Evaluation of valve designs



*1 : perimeter length (see eq.(8))

*2 : 0 ; activated 1 ; deactivated

*3 : number of usage in actual desig

*4 : see the illustrations

Figure 4 Data base structure for the design of valve system

	σ_{inf}	Mach number	σ_b	t_c	V_{imp}
D(*1)	++(*3)	--	-	0	-
L	0	-	+	+	+
W	0	+	-	0	0
t	--	+	-	-	-
stiffness	0	+	-	-	0
stop(*2)	0	-	+	0	+

(*1) D : diameter of circular port
L,w,t : length, width, thickness of cantilever valve
(*2) effect of the stop height (only when the stopper is effective)
(*3) + : proportional ++ : strongly proportional
-, -- are the same notion but inversely
0 : no effect or unclear relation

Table 1 : Effect of design parameters

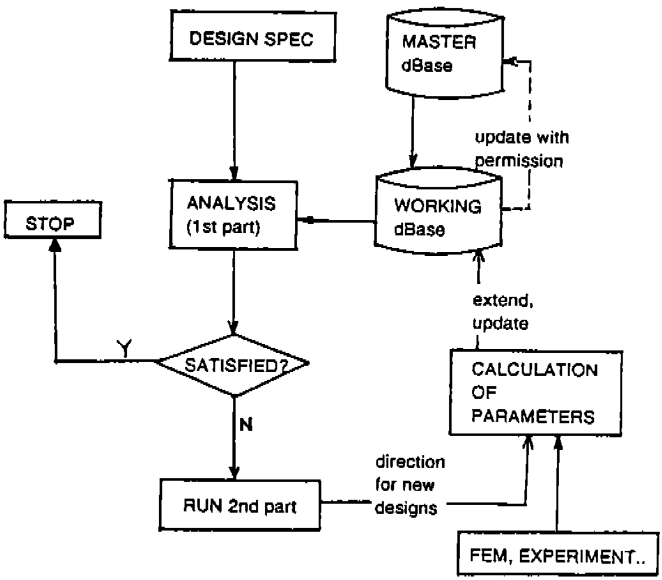


Figure 5 Overall procedure of expert system design

```
There is no acceptable design for SUCTION valve.
     Select 1 = see top three designs
            9 = quit
     selection = 1

  ** TOP THREE DESIGNS FOR SUCTION VALVE
```

PORT	VALVE	GEO L	GEO W	CONS. Dm	CONS. Dn	INF stress	STOP	MACH NO	BEND. stress	clos. time	IMP. vel.	NO VIOL	SCORE
9	3	0	0	0	0	.47	.55	1.34	1.08	.64	1.00	2	4.53
10	3	0	0	1	1	.53	.50	1.21	.97	.64	.90	3	4.24
8	3	0	0	0	0	.42	.62	1.49	1.20	.64	1.11	3	4.86

```
      Return 1 = select (9,3) as the base for new designs
             2 = select (8,3) as the base for new designs
             3 = select (7,3) as the base for new designs
             4 = show the next three best designs
             5 = exit to discharge side
             9 = exit
      ** SELECTION = 1
  ( RECOMENDATIONS ) : Try one or more of the followings.
   FROM THE DESIGN (9,3),
   (1) Enlarge the port diameter.
   (2) Reduce stiffness of the valve.

      Return 2 = select (8,3) as the base for new designs
             3 = select (7,3) as the base for new designs
             4 = show the next three best designs
             5 = to discharge side
             9 = exit
      ** SELECTION = 5


There is no acceptable design for DISCHARGE valve.
     Select 1 = see top three designs
            9 = quit
     selection = 1

  ** TOP THREE DESIGNS FOR DISCHARGE VALVE
```

PORT	VALVE	GEO L	GEO W	CONS. Dm	CONS. Dn	INF stress	STOP	MACH NO	BEND. stress	clos. time	IMP. vel.	NO VIOL	SCORE
9	2	0	0	0	0	.73	1.00	.98	1.56	.92	.71	1	4.89
6	1	0	0	0	0	.91	1.00	1.42	1.17	.35	.53	2	4.43
5	1	0	0	0	0	.78	1.00	1.61	1.17	.31	.53	2	4.49

```
      Return 1 = select (9,2) as the base for new designs
             2 = select (6,1) as the base for new designs
             3 = select (5,1) as the base for new designs
             4 = show the next three best designs
             9 = exit
      ** SELECTION = 1
  ( RECOMENDATIONS ) : Try one or more of the followings.
   FROM THE DESIGN (9,2),
   (1) Enlarge the port diameter.
   (2) Reduce stiffness of the valve.

      Return 2 = select (6,1) as the base for new designs
             3 = select (5,1) as the base for new designs
             4 = show the next three best designs
             9 = exit
      ** SELECTION = 9
```

Figure 6 Example ; Design with expert system

6-1 Running design improvement part

SUCTION VALVE

PORT	VALVE	GEO L	GEO W	CONS. Dm	CONS. Dn	INF stress	STOP	MACH NO	BEND. stress	clos. time	IMP. vel.	NO VIOL	SCORE
13	13	0	0	0	0	.70	.27	.99	.62	.64	.49	0	3.45
12	13	0	0	0	0	.64	.29	1.07	.67	.64	.53	1	3.55
11	13	0	0	0	0	.58	.31	1.15	.71	.64	.56	1	3.65
10	13	0	0	0	0	.53	.33	1.25	.77	.64	.60	1	3.79
9	13	0	0	0	0	.47	.37	1.37	.84	.64	.66	1	3.99
8	13	0	0	0	0	.42	.40	1.52	.93	.64	.73	1	4.24
13	12	0	0	0	0	1.10	.47	.91	.87	.81	.68	1	4.36
12	12	0	0	0	0	1.01	.52	1.00	.95	.81	.75	1	4.51
15	13	0	0	1	1	.83	.24	.87	.56	.64	.44	2	3.35
14	13	0	0	1	1	.76	.26	.93	.59	.64	.46	2	3.39

DISCHARGE VALVE

PORT	VALVE	GEO L	GEO W	CONS. Dm	CONS. Dn	INF stress	STOP	MACH NO	BEND. stress	clos. time	IMP. vel.	NO VIOL	SCORE
10	12	0	0	0	0	.82	1.00	.90	.92	.80	.35	0	3.84
11	12	0	0	0	0	.91	1.00	.81	.92	.88	.35	0	3.93
8	2	0	0	0	0	.66	1.00	1.12	.78	.41	.35	1	3.36
9	2	0	0	0	0	.73	1.00	1.00	.78	.46	.35	1	3.37
7	2	0	0	0	0	.58	1.00	1.27	.78	.36	.35	1	3.43
6	2	0	0	0	0	.51	1.00	1.44	.78	.31	.35	1	3.53
8	3	0	0	0	0	.42	1.00	1.12	.97	.64	.44	1	3.59
9	3	0	0	0	0	.47	1.00	1.00	.97	.71	.44	1	3.60
7	3	0	0	0	0	.37	1.00	1.27	.97	.56	.44	1	3.64
5	2	0	0	0	0	.44	1.00	1.63	.78	.28	.35	1	3.65

Figure 6 Example ; Design with expert system

6-2 Result of new designs

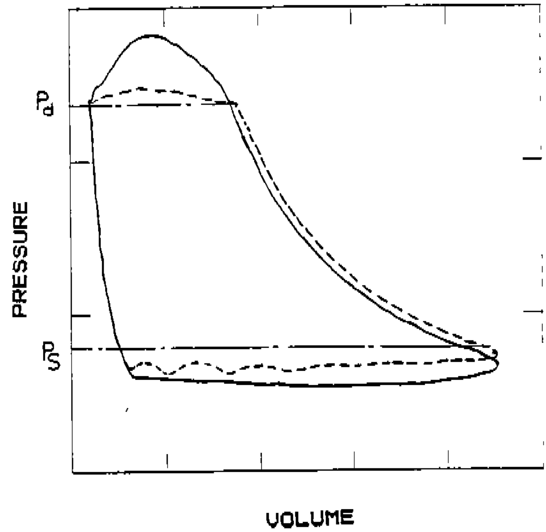


Figure 7 P-V diagrams of old and new designs, ———,old design, -----, new design