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A Bar and Ring Valve Model for Use in Daily Design Work

G. W. Gatecliff

A BAR AND RING VALVE MODEL FOR USE IN DAILY DESIGN WORK

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ABSTRACT

An outline of a procedure used to design bar and ring valves is presented and discussed. The model differs from a simulation in that it simplifies many peripheral aspects and deals rigorously with only the valve and the forces acting on it. Inputs are limited to data describing initial conditions, pertinent geometry, operating conditions, and the structural characteristics of the valve and/or compressor. Output consists of graphs showing the deflection of the valve as a function of time and the mass flow history through the ports. Program execution typically requires less than one half hour on a 32 bit minicomputer.

INTRODUCTION

Bar and ring valves are widely used in hermetic compressors. The dynamic behavior of these components is determined by their mass and stiffness characteristics, the fluid forces acting on them, and the physical constraints limiting their travel. The adequacy of a design is measured by the ability of the valve to function quietly and efficiently for extended time periods under a wide range of operating conditions.

The procedure outlined herein allows comparison of the performance characteristics of valve designs without the need to fabricate and test prototypes. It has the advantage of quickly providing a detailed prediction of time-dependent cyclic behavior. It allows the performance of new designs to be compared with each other and to existing valves. The time for a single evaluation is measured in hours rather than months. The purpose is to increase the success of new valves placed on life test, thereby reducing both the time and cost required to qualify a design.

MATHEMATICAL MODEL

The valve is assumed to be a plate of uniform thickness described by the following form of the plate vibration equation (1):

$$D_e \nabla^4 w + \partial^2 w/\partial t^2 = F_{jk}(t)\,\delta(x-x_j)\,\delta(y-y_k) \quad (1)$$

The solution to equation (1) is obtained with the aid of finite element techniques.

MESH GENERATION

Application of the finite element method can be complex and time consuming. Many opportunities exist for errors to be introduced into the process. Computer assisted mesh generation can be used to help minimize this problem.

The approach outlined here begins with the generation of a geometric representation of a quarter section of the valve based on the design parameters shown in Figure 1. The interior of the valve is then

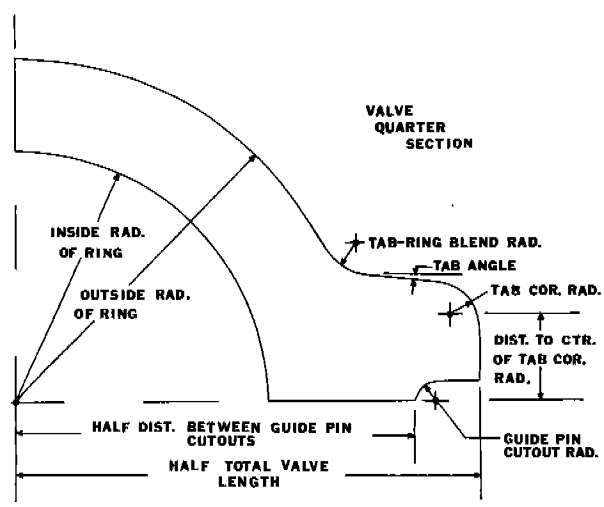


Figure 1

automatically partitioned into a number of quadrilateral regions which, in turn, are subdivided into a series of smaller triangles as shown in Figures 2 and 3.

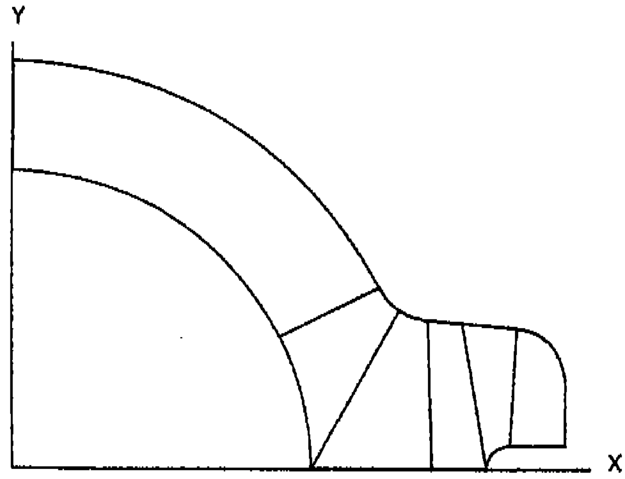


Figure 2

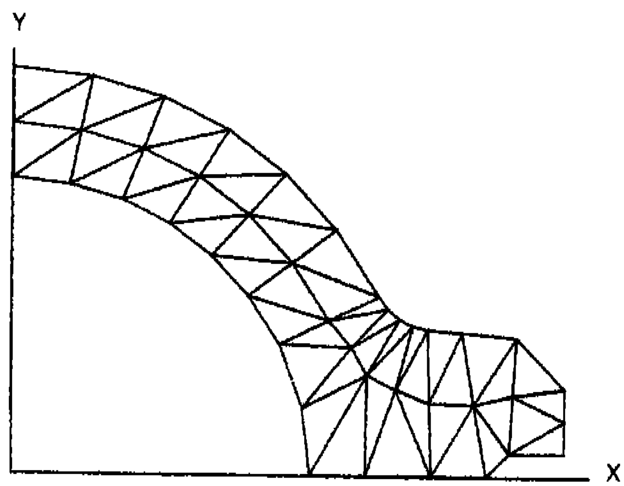


Figure 3

Material properties and boundary conditions are entered with a series of special programs. A model of one half the valve can be produced by combining the original quarter section with its mirror image. The result of these operations is shown in Figure 4.

FINITE ELEMENT ANALYSIS

The element mass and stiffness matrices used in this study (2) employ an eighteen degree-of-freedom plate bending triangle with the following degrees of freedom at each node:

1. Deflection z
2. Slope $\partial z/\partial x, \partial z/\partial y$
3. Curvature $\partial^2 z/\partial x^2, \partial^2 z/\partial y^2$
4. Twist $\partial^2 z/\partial x \partial y$

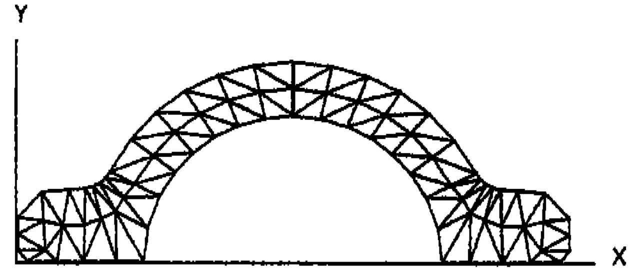


Figure 4

The global mass [Mg] and stiffness [Kg] matrices are assembled from the individual element mass and stiffness matrices.

The dynamic behavior of the valve is determined by monitoring a strategically selected subset of master nodes within the mesh. This permits a substantial reduction in the computational resources required to perform the analysis. The number of mesh variables is reduced by employing Gaussian Elimination, as suggested in the Guyan Reduction method. This procedure has the effect of lumping mass and stiffness at the locations of the master nodes shown in Figure 5.

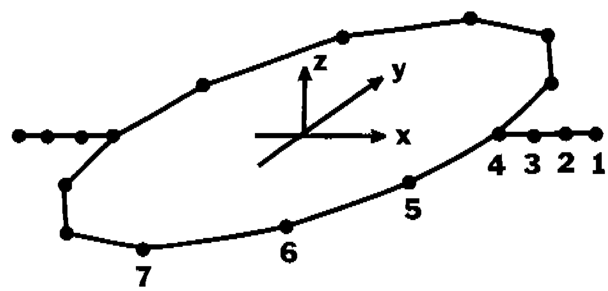


Figure 5

BOUNDARY CONDITIONS

The dynamic behavior of the valve is influenced by the restrictions imposed on its motion by the structure in which it is mounted. Figure 6 illustrates the geometry and important mounting dimensions associated with the valve of Figure 1. Free-free boundary conditions apply at both ends of the valve as described mathematically by the following expressions.

$$\partial^2 z(0,t)/\partial x^2 = 0 \qquad \partial^3 z(0,t)/\partial x^3 = 0$$

$$\partial^2 z(L,t)/\partial x^2 = 0 \qquad \partial^3 z(L,t)/\partial x^3 = 0$$

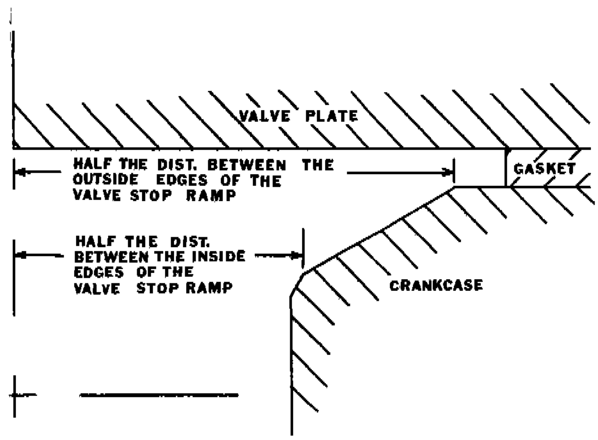


Figure 6

The deflection of the valve at each of the master nodes is constrained as follows:

$0 \leq$ displacement $\leq$ stop height(if it exists)

The interaction of the valve with its seat and stop is modeled by a "bounce" type of analysis such that the velocities before and after impact are related by the following expression:

$$\dot{w}_{\text{after impact}} = -CFR\,\dot{w}_{\text{before impact}}$$

A bounce against the stop in two successive time increments causes the program to switch from a mode wherein deflection is determined as a function of time to a mode in which the time dependent constraint force becomes the unknown. The analysis continues in this mode until the constraint force undergoes a change in sign, at which time it reverts to the original format. The valve then moves away from the restraint or impacts with it. Either way the process begins anew as outlined above.

EIGENVALUE SOLUTION

The following generalized eigenvalue problem is solved to yield the natural freqiencies (ω) and mode shape (Z).

$$\omega^2 [Mg]\ Z = [Kg]\ Z$$

Iterative solution techniques were choosen because they efficiently predict dominant frequencies while preserving the banded nature of the problem. The natural frequencies and mode shapes calculate by this procedure are used to predict the time dependent motion of the valve.

COMPRESSOR MODEL

The thermo-fluids model developed previously (3) is utilized here. The fluid network consists of three elements; the discharge cavity, cylinder volume, and suction plenum. The pressures in both volumes adjacent to the cylinder are held constant in order to simplify and shorten the analysis.

The operation of the compressor is modeled by dividing each revolution of the crankshaft into a series of 180 discrete time steps. In order to start the process, a set of initial conditions must be specified that approximately reflect the state of the valve and the conditions within the cylinder at a given point in time. Discharge valve closing is a suggested starting point when a prediction of suction valve motion is sought and vice versa. In this case, the quantities to be supplied, and a realistic first approximation of each, are as follows:

	Suction	Discharge
Location of Valve Closing	30 ABC	10 ATC
Cylinder Pressure	Avg. Suction Plenum Pressure	Avg. Discharge Plenum Pressure
Cylinder Temperature	Avg. Suction Plenum Temperature	Avg. Discharge Plenum Temperature

Repeated alternate modeling of suction and discharge valves will allow the designer to quickly determine the crankshaft location at which each valve closes.

Starting with this information, plus a geometric description of the compressor and the finite element mode shapes and natural frequencies describing the valve, the model produces a time ordered prediction of the following quantities:

1) Cylinder pressure

2) Valve displacement

3) Valve tip velocity

4) Pressure difference across the ports

5) Effective port area

6) Port velocity

7) Mass flow through the ports

8) Mass in the cylinder

In addition, the model outputs the following information once the cycle has been completed.

1) Average port velocity

2) Average pressure drop across the ports

3) Net mass transfer

4) Work expended during the time the valve is open

5) Duration of valve opening

6) A measure of valve efficiency

OUTPUT GRAPHICS

The time dependent behavior of the valve can also be displayed in the form of computer generated plots and animations. A typical set of output plots corresponding to the locations number 1 through 7 in Figure 5 are shown below in Figures 7 through 13.

Images that appear in rapid succession on a cathode ray tube can be used to provide an animated display of valve motion (4). Each of the images labeled 14 through 40 is a separate valve position or alternate viewing position selected from the many required to depict one cycle of valve motion. Figures 14, 15 and 16 show a side, end and perspective view of the valve at

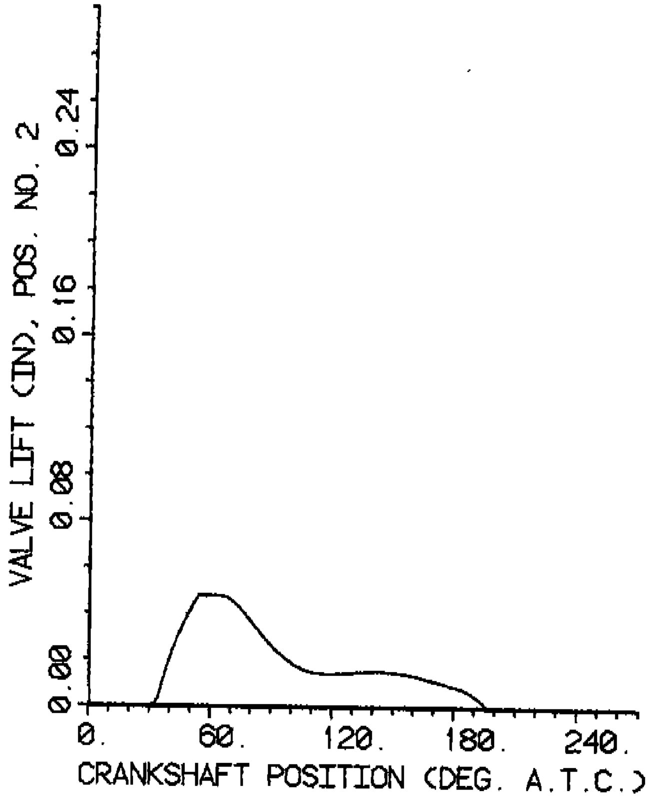


Figure 8

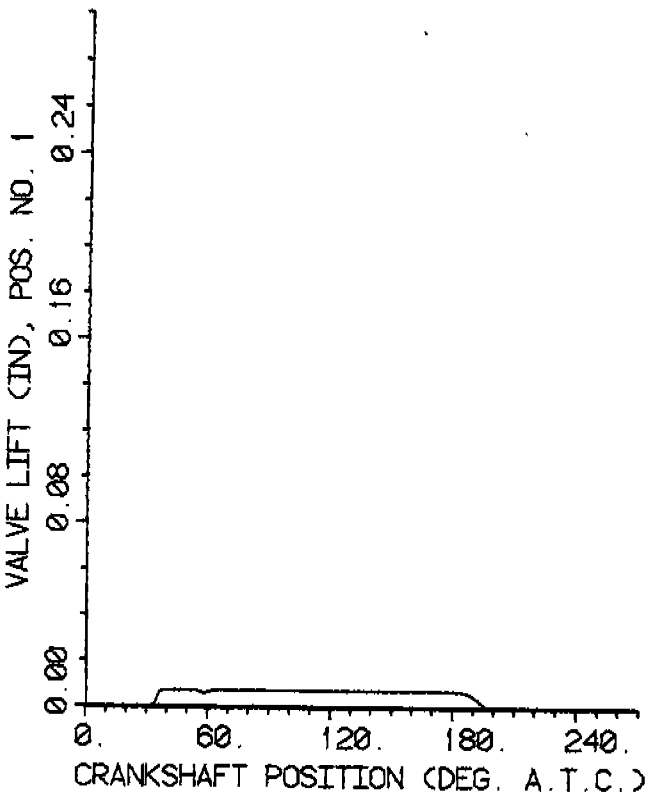


Figure 7

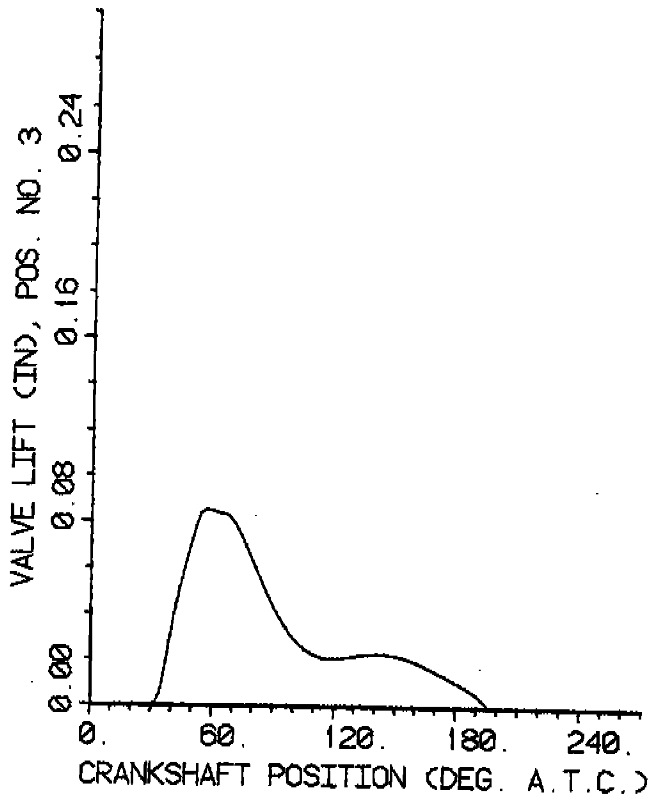


Figure 9

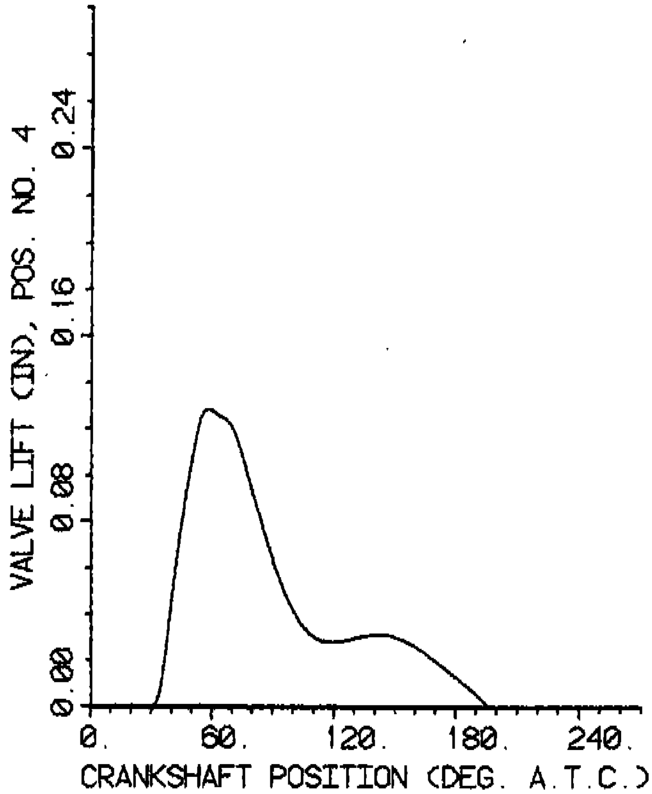


Figure 10

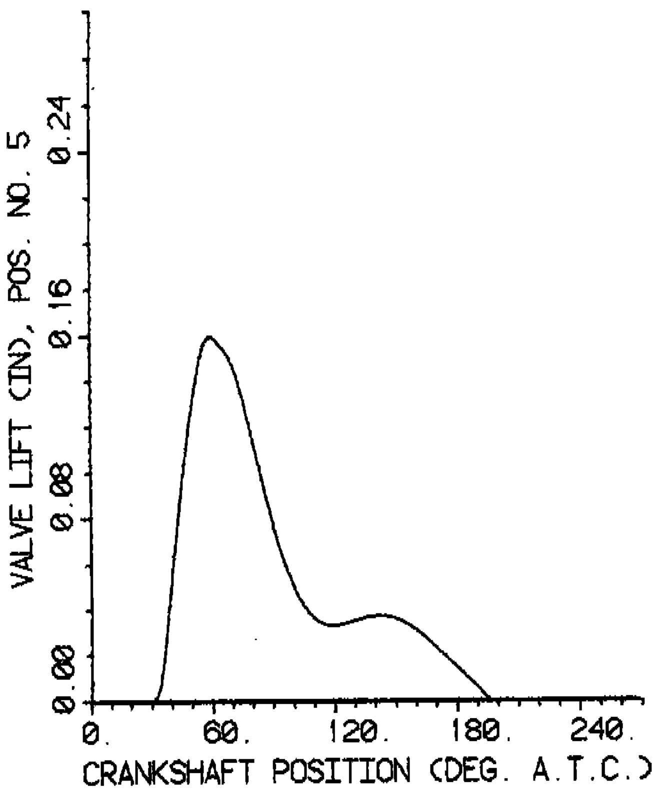
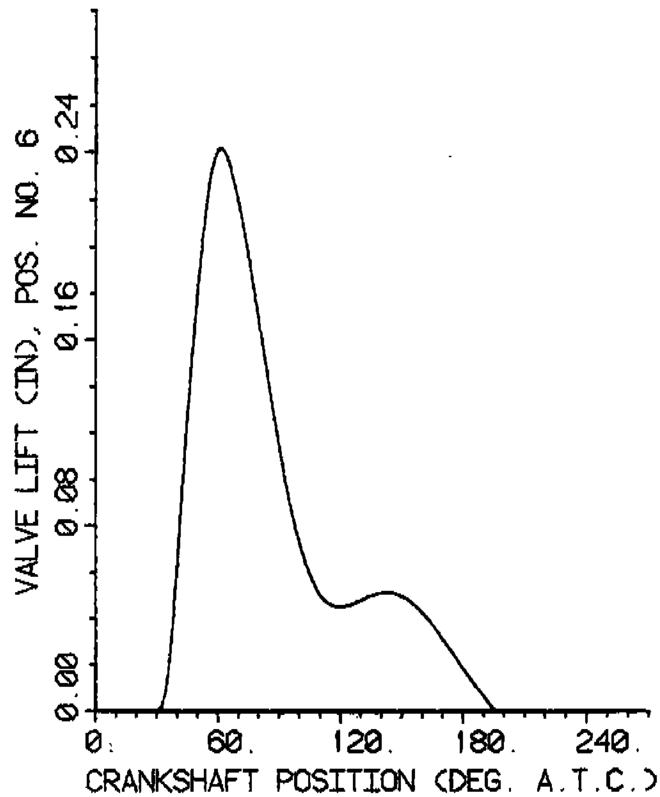


Figure 11



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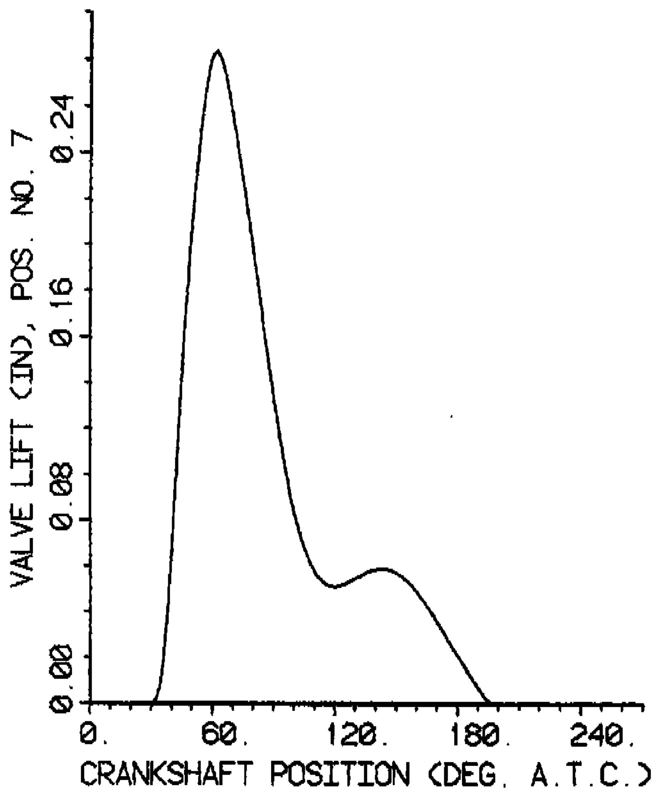

Figure 13

rest on the valve plate. The V shaped marks denote the valve stops.

Figure 14

Figure 15

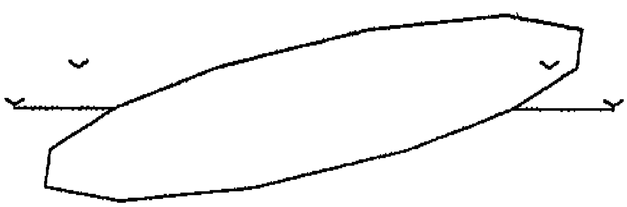

Figure 16

Figures 17 through 31 depict the opening surge of the valve.

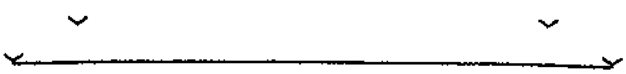

Figure 17

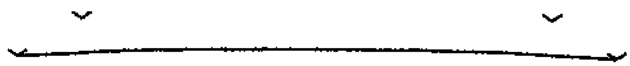

Figure 18

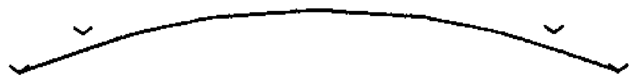

Figure 19

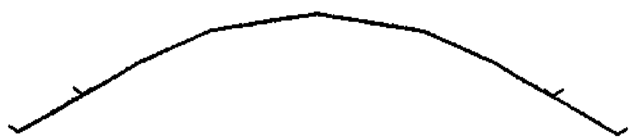

Figure 20

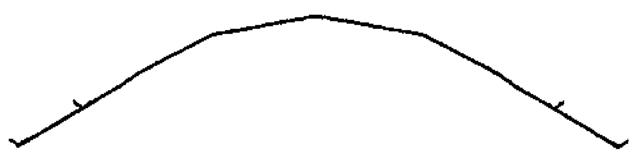

Figure 21

Figure 22

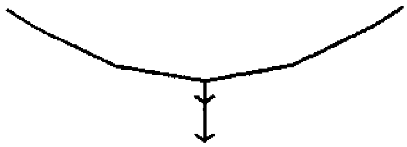

Figure 26

Figure 23

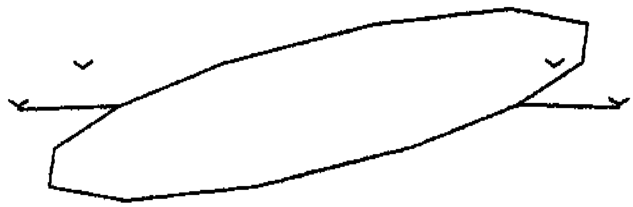

Figure 27

Figure 24

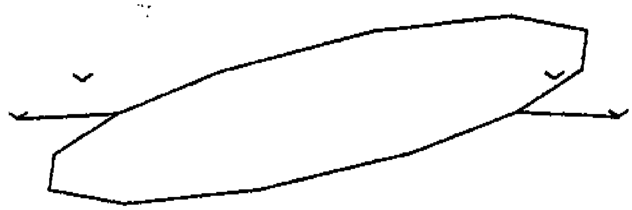

Figure 28

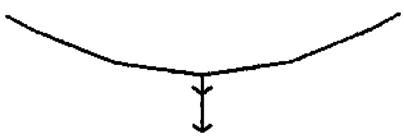

Figure 25

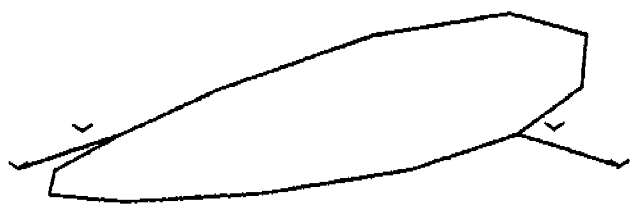

Figure 29

Figure 30

Figure 31

The valve falls back toward the valve plate as a result of "overshooting" during the initial stages of the opening process.

Figure 13 indicates the valve reverses its direction and begins to move away from the valve plate once again at a crankshaft position of approximately 120 Deg. A.T.C. Figures 32 through 40 document this event.

The subject valve operates in a very smooth and continuous manner. Impacts against the stops and/or valve plate do not produce violent reactions or occur in large numbers.

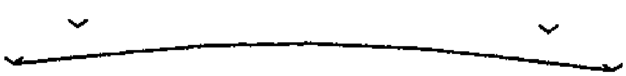

Figure 32

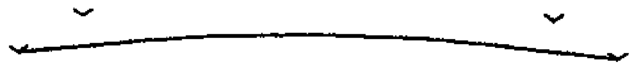

Figure 33

Figure 34

Figure 35

Figure 36

Figure 37

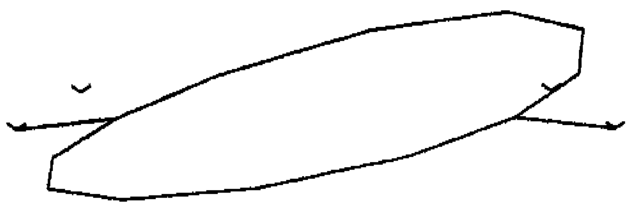

Figure 38

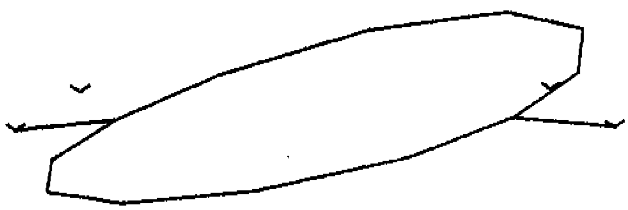

Figure 39

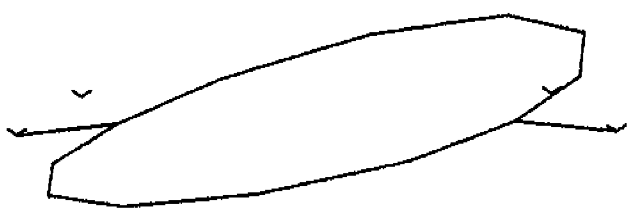

Figure 40

CONCLUDING REMARKS

The procedure outlined here is a generalized technique that can be applied to valves of arbitrary shape. Computer graphics permits the results of these calculations to be readily comprehended.

ACKNOWLEDGEMENTS

The author would like to note the contributions of Mr. G.C. Grinner and Ms. E. D. Kock who were responsible for creating and/or maintaining the finite element software used to perform this analysis.

LIST OF SYMBOLS

$\delta(x-x_j)(y-y_k)$ - Kronecker delta; defined as 1 for $x=x_j$ and $y=y_k$ and 0 for all other values of x and y

CFR - Coefficient of restitution

D_e - Flexural regidity

F_{jk} - Force at x_j and y_k

p - Density

t - Time

x - Distance along the length of the valve

y - Distance across the valve

w - Valve deflection

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