Optimisation of Compressor Valve Design Using a 'Complex' Method

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ABSTRACT

In recent years a number of mathematical models have been developed which simulate reciprocating compressor performance and valve behaviour. Such a model (4), has been used with a 'complex' optimisation procedure to optimise the design of spring loaded ring plate valves in a reciprocating air compressor. Features of the procedure are discussed, such as the handling of constraints, the sensitivity of the optimum to changes in the design parameters and the search for a 'global' optimum. A corresponding experimental study of the air compressor was conducted in an attempt to establish the extent of the validity of the procedure.

In general the direction of change in the values of the valve parameters in the optimised design was such as would have been expected from intuition and experience. Small improvements predicted in compressor performance were partially confirmed in the experimental tests.

INTRODUCTION

In the complex method developed by Box (1), a number of points, k, which lie within specified constraints are generated in a pseudo-random fashion. An objective function, F(x), is calculated at each of the points and the point with the lowest value of objective function is identified. This point is then moved in a direction through the centroid of the remaining points by a distance of $(1+\alpha)$ times that of its original displacement from the centroid. (The value of α used in the computations was 0.3) If at the new location the point no longer has the lowest value of objective function and is within the search area, it is accepted and attention is turned towards the point with the next lowest value. By continually seeking improvements in the worst point, the complex of points moves through the search area towards the optimum.

If, however, the point after moving either remains the worst point or lies outside the search area boundaries imposed by the constraints, it is not accepted. When the moved point lies outside an explicit constraint (i.e. a constraint on one of the independent variables) it is moved a small distance inside the violated constraint and then accepted. If the new point either remains the worst point or lies outside an implicit constrant (i.e. a constraint on a function of the independent variables) the point is moved in steps halfway towards the centroid until the condition is remedied. If after a specified number of steps the point is still the worst point, the centroid is tested, and if the centroid is found to be the worst point (i.e. if the search area is a non-convex space), the strategem of Box fails, as has been noted by Guin (2) and Friedman and Pinder (3). To circumvent this problem we have modified the method by Box to move the rejected worst point in steps halfway towards the best point rather than to the centroid, until an improvement occurs.

Convergence is assumed to have occurred when for a specified number of consecutive iterations, the objective function at new points satisfying all the above conditions lies within a specified range of difference from the best value.

The modified method was used to optimise the design of the self-acting valves in a reciprocating air compressor. The mathematical model employed (4) describes the compressor, its valves and the operating conditions, by simultaneous differential equations which apply during the suction and discharge processes. The criterion of performance chosen for optimisation, the objective function F(x), was effectively that of "the greatest gas throughput for the least power input" defined by $F(x_1 x_2 \ldots x_N)$

$$= 100 \times \frac{\text{volumetric efficiency}}{1 + \dfrac{\text{valve losses}}{\text{thermodynamic work input for the adiabatic cycle}}}$$

The choice of the design parameters which are to be allowed to change in the optimisation process, the independent variables, is a matter of judgment, too many would obscure the influence of their individual contribution to an optimised design and too few could render the optimisation incomplete.

Certain basic dimensions (r, l, Ap, c) of the compressor were considered to be fixed. The single stage compressor used had a cylinder bore 6 in and stroke $4\frac{1}{2}$ in, and was fitted with single annular ring plate valves, each backed by three coil springs, at both suction and discharge. Twelve independent valve variables were chosen initially, (AV, AI, HO, WV, K, LD for both suction and discharge). To ensure that the optimised design was practicable each parameter was given an upper and a lower constraint value, these values being fixed arbitrarily above and below the (reference) values for the present design.

Initial trials were of limited success. The procedures placed most parameters on either the upper or lower value of their (explicit) constraints (eg. permitted lift on the upper, valve spring preload on the lower). Improvements in the objective function were predicted but were accompanied by unacceptably high values of valve plate impact velocity. Constraints were therefore imposed on this parameter and as a consequence the parameters being optimised no longer assumed their upper and lower constraint values. Improvements in the objective function of up to 8% were achieved. These trials demonstrated that using a 'complex' optimisation procedure, a combination of these parameters could be found which predicted significant improvement in compressor performance.

Since the physical size of the valves was restricted by the size of the cylinder bore, AV and AI were removed from the list of independent variables. This simplified the optimisation process and made more practical the experimental testing of optimised designs. The process predicted that improvements would be obtained with increased permitted lift and valve plate mass, reduced spring stiffness and with spring preload reduced to approximately zero. Experimental tests did not confirm this, mainly because the mathematical model had failed to predict the very late suction valve closure observed by experiment.

The number of independent variables was further reduced by excluding the valve plate mass WV and, since the valve lift was prevented from becoming very large by the arbitrary constraint on impact velocity, by excluding the maximum permitted valve lift, H_O. There thus remained only four parameters free to vary, i.e. the spring stiffness and preload for both suction and discharge valves (KS, KD, LDS, LDD).

Optimisations were performed with the fixed parameters at various values to show the sensitivity of the objective function to changes in these parameters. They also afforded an opportunity to investigate the optimisation procedure itself, its ability to converge on the 'global' (highest) optimum in a non-convex space, the importance of the number of points in the complex, the effectiveness of the method used to apply the constraint on valve plate impact velocity and the sensitivity of the objective function to changes in the independent variables.

LOCAL AND GLOBAL OPTIMUM

Figure 1 illustrates results of optimisations using four parameters (KS, KD, LDS, LDD) for a number of arbitrary values of WVS. At values of WVS/WVS_r between 1.2 and 1.5, with 10 points in the complex, two distinct curves are apparent for both F(x) and KS. This indicates that the procedure was converging to two completely separate optima in this region. In Figure 2 the curve of F(x) against KS/KSr for WVS/WVSr = 1.52 and with ten points in the complex, the two optima, a global and a local, are apparent; the search area is thus non-convex.

Also illustrated in Figure 2 is the path taken to the optimum by the centroid of the complex for the optimisation with WVS/WVSr = 1.52. The initial 10 points in the complex are well distributed within the search area. After 20 iterations, 9 of the points (Nos 2 - 10) have converged to the local optimum (at KS/KSr $\doteq$ 1.6), but one point (No 1) has - fortuitously - landed high enough on the slope of the global optimum (at KS/KSr $\doteq$ 0.9) to be the best point. At this stage of the optimisation the value of F(x) at the centroid of the complex is lower than at any of the other points (the centroid is somewhere in the trough shown on Figure 2) and would have led to premature convergence or failure of the method by Box. However, using our modified method, the single point near the global optimum was able to pull convergence across the deep trough towards the global optimum. When the initial number of points in the complex was increased from 10 to 20 all optimisations converged to the global optimum.

The tendency to converge to a local optimum is a function of the shape of the search area, the initial number of points in the complex, and their distribution. In general, the larger the number of points, the more completely the search area will be scanned before convergence to a particular optimum begins. This increases the likelihood of the global optimum being located, but at the expense of increased computer time.

IMPACT VELOCITY CONSTRAINT

When a point in the complex produced a value of impact velocity which was outside the imposed constraint value, the point had to be rejected as unacceptable; this was effected by subtracting the numerical value (in ft/s x 100) of the impact velocity from the value of the objective function, so ensuring that the value became negative. This led inevitably to rejection of the point and sent the search in a direction away from, or along the constraint. Though simple the method was found to be successful.

A typical constrained path to the optimum is shown in Figure 3. The path first moved away from the constraint as initial points violating the constraints were moved into the permissible region and then, because the optimum lay outwith the permissible region, the search returned to the constraint and moved along it until no further improvement was obtained. A small increase in valve plate mass had a significant effect on the position of the constraint within the search area: as is shown in Figure 3 changing WVS/WVSr from 1.0 to 1.22 almost completely removed the constraint from the search area. This indicated that the impact velocity was very sensitive to changes in valve plate mass.

PARAMETER SENSITIVITY

The effect on convergence of starting with different initial complexes was investigated and the results are shown in Figure 4. At a value of WVS/WVSr of 1.65, the centroid of three different complexes Q, R and S moved quickly towards the same optimum and produced the same values of parameters for the suction valve; this is shown in Figure 4A. The parameters for the discharge valve for the same tests finished with widely separated values (Figure 4B), thus indicating a much greater sensitivity of the objective function to changes in suction valve spring stiffness and preload than to the equivalents for the discharge valve.

At convergence the values of the parameters for the discharge valve at the optimum point were markedly different to the values at the centroid of the complex. The discharge valve parameters had not fully converged although changes in the value of the objective function between iterations had indicated that convergence had taken place. This suggested a method for testing the sensitivity of F(x); namely, if the points in the complex showed a wide dispersal of values for a particular parameter at convergence then the objective function was insensitive to this parameter. The dispersal was quantified by calculating the standard deviation, σ , of these values.

In all the tests the value of σ was greater for the parameters for the discharge valve than for the equivalent parameter for the suction valve. Also for each valve, the values of σ for preload were less than the values for spring stiffness. Some typical values are given in Table 1.

WVS/WVS_r	LDS/LDS_r	KS/KS_r	LDD/LDD_r	KD/KD_r
	$\sigma \times 10^4$	$\sigma \times 10^4$	$\sigma \times 10^4$	$\sigma \times 10^4$
0.78	55	237	1744	3732
1.0	80	309	1594	2267
1.22	304	862	2148	5904
1.45	275	874	1755	5633

TABLE 1 : NON DIMENSIONALISED VALUES OF STANDARD DEVIATION

To study the sensitivity of F(x) to variables other than the independent variables the impact velocity constraints were increased sufficiently to effectively remove them from the search area. Figures 5 and 6 show the percentage change in the objective function and suction valve impact velocity for a given percentage change from the reference values of a number of parameters. Each curve was obtained by optimising four variables (KS, KD, LDS, LDD) with one parameter whilst the other parameters were held at their reference values. The graphs confirm what was already known from intuition and experience: namely that alteration of a design to give improved thermodynamic performance often carried some form of penalty. Many of the changes which produced an improvement in the objective function resulted in an increase in suction valve impact velocity, indicating that a higher performance might be obtained but at the expense of valve life. Examples of these types of changes are shown in the graphs of suction and discharge valve lift and the suction valve port and plate areas.

An increase in compressor speed reduced the value of the objective function and increased the suction valve velocity and optimum spring stiffness; a decrease had the opposite effect. An increase in discharge pressure reduced, and a decrease increased, the objective function, but had little effect on valve velocity or optimum spring stiffness. Assuming that impact velocity is related to valve life, then for a compressor which has to operate at off design conditions an increase in pressure ratio would be less harmful than an increase in speed. The objective function did not alter with change of suction valve plate mass but, as was discussed in relation to Figure 3, the impact velocity was very sensitive to this parameter. The graph of valve coefficient of discharge indicates that a high value of coefficient was beneficial in two ways, by increasing the objective function and decreasing the impact velocity.

The method is being extended to optimise the design of the compressor, in which swept volume, piston diameter to crank radius ratio and operating speed are also variables. These variables embody opposing factors which make intuitive optimisation impossible.

CONCLUSIONS

Improvements in the performance of a reciprocating compressor may be predicted using a computer simulation model and an optimisation procedure. If an upper limit can be stipulated for valve impact velocity the method will determine the values of parameters in the valve design which will result in maximum thermodynamic performance within the constraints imposed by the designer.

NOMENCLATURE

AID	Discharge valve port area
AIS	Suction valve port area
Ap	Piston area
AVD	Discharge valve plate area
AVS	Suction valve plate area
CD	Coefficient of discharge
c	Clearance volume
F(x)	Objective function
HOD	Discharge valve; maximum permitted lift
HOS	Suction valve; maximum permitted lift
k	Initial number of points in a complex
KD	Discharge valve spring stiffness
KS	Suction valve spring stiffness
l	Length of connecting rod
LDD	Discharge valve spring preload
LDS	Suction valve spring preload
PD	Discharge pressure
RPM	Rotational speed of compressor
r	Radius of crank
r(suffix)	Reference
VS	Suction valve plate impact velocity
VS_{lim}	Constraint on VS
WVD	Mass of discharge valve plate
WVS	Mass of suction valve plate

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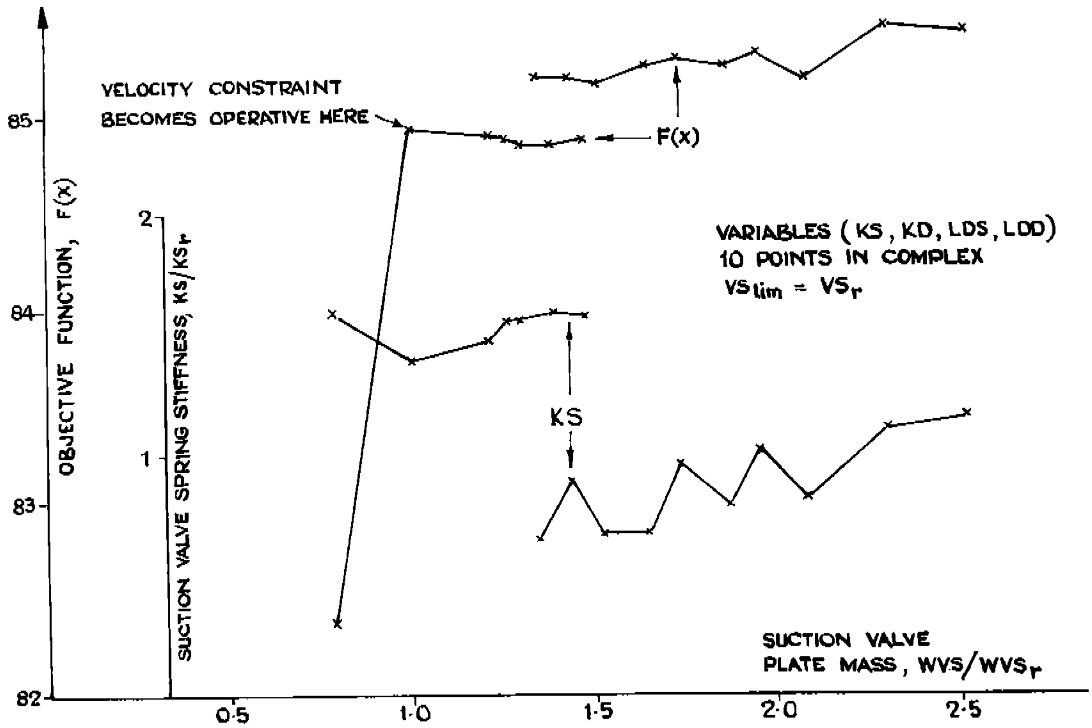

FIG. 1. VARIATION OF OPTIMISED VALUES OF SUCTION VALVE SPRING STIFFNESS AND OBJECTIVE FUNCTION AGAINST MASS OF SUCTION VALVE PLATE.

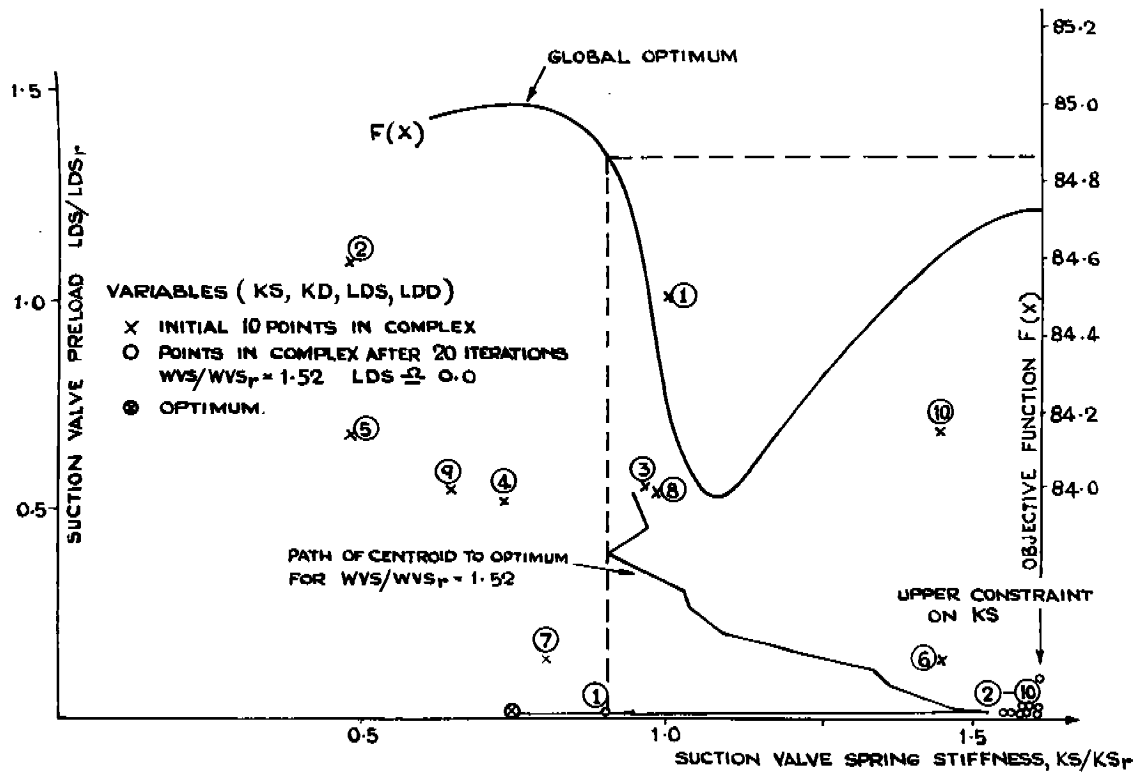

FIG. 2. GLOBAL AND LOCAL OPTIMUM IN A NON-CONVEX SEARCH AREA.

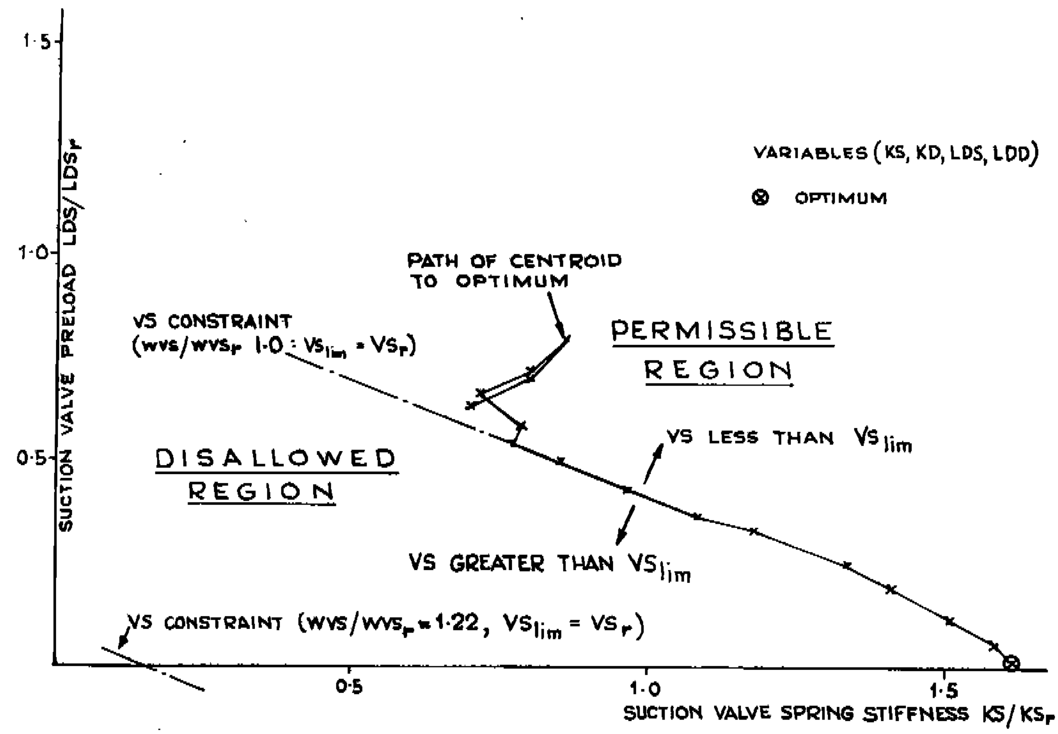

FIG. 3. THE EFFECT OF THE VELOCITY CONSTRAINT ON THE SEARCH PATH.

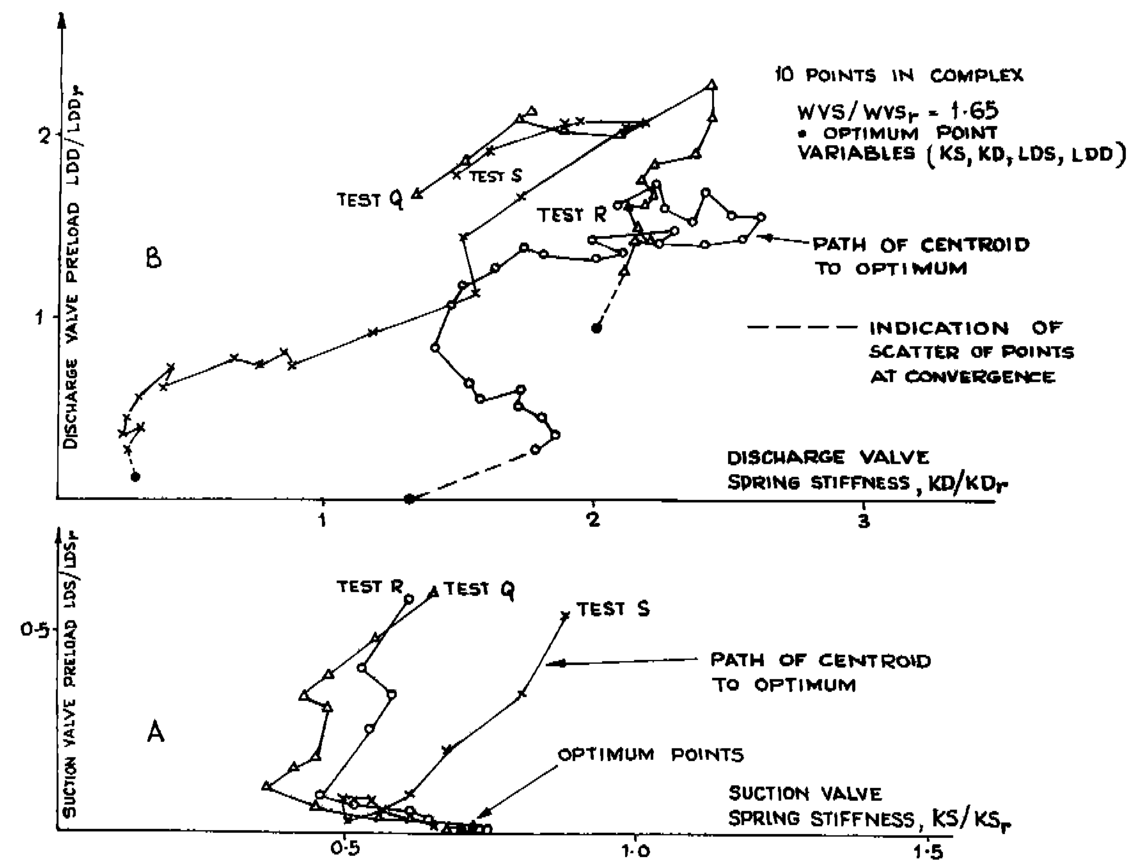

FIG. 4. OPTIMISATION PATHS FOR THREE DIFFERENT INITIAL COMPLEXES.

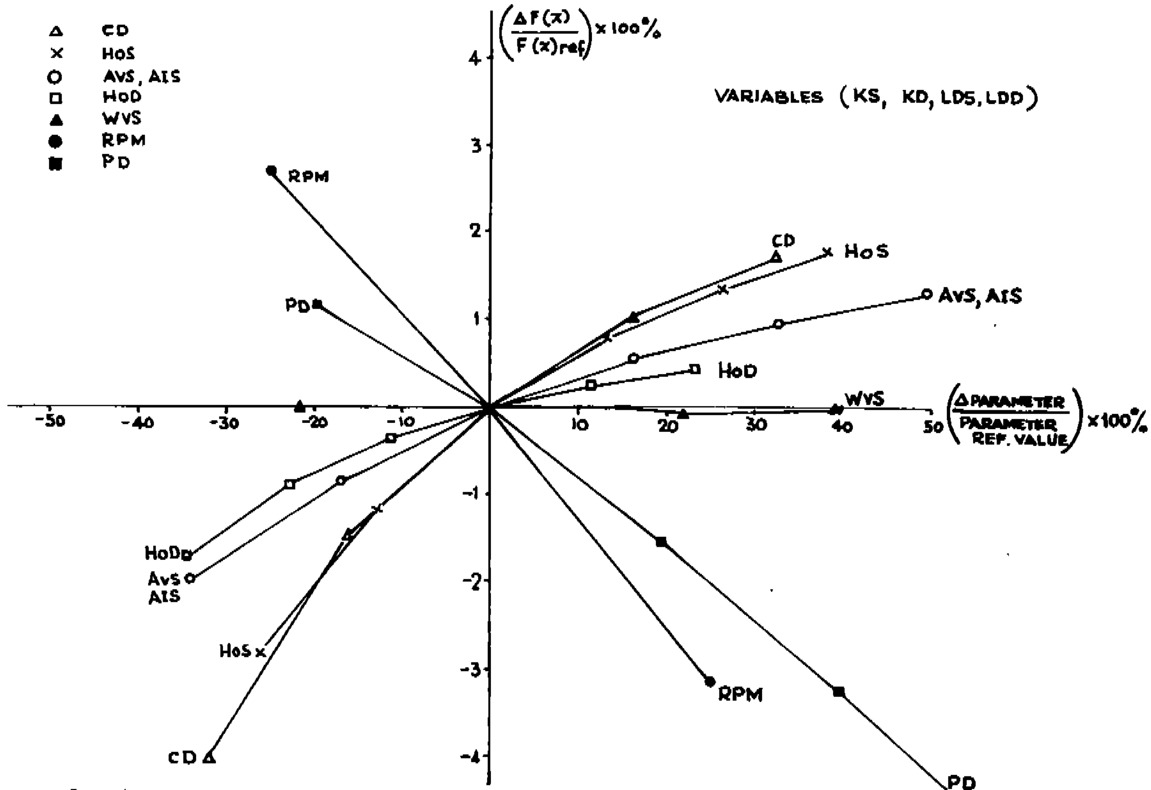

FIG. 5. THE RELATIVE CHANGE IN THE OPTIMISED VALUE OF OBJECTIVE FUNCTION AGAINST RELATIVE CHANGES IN OTHER PARAMETERS.

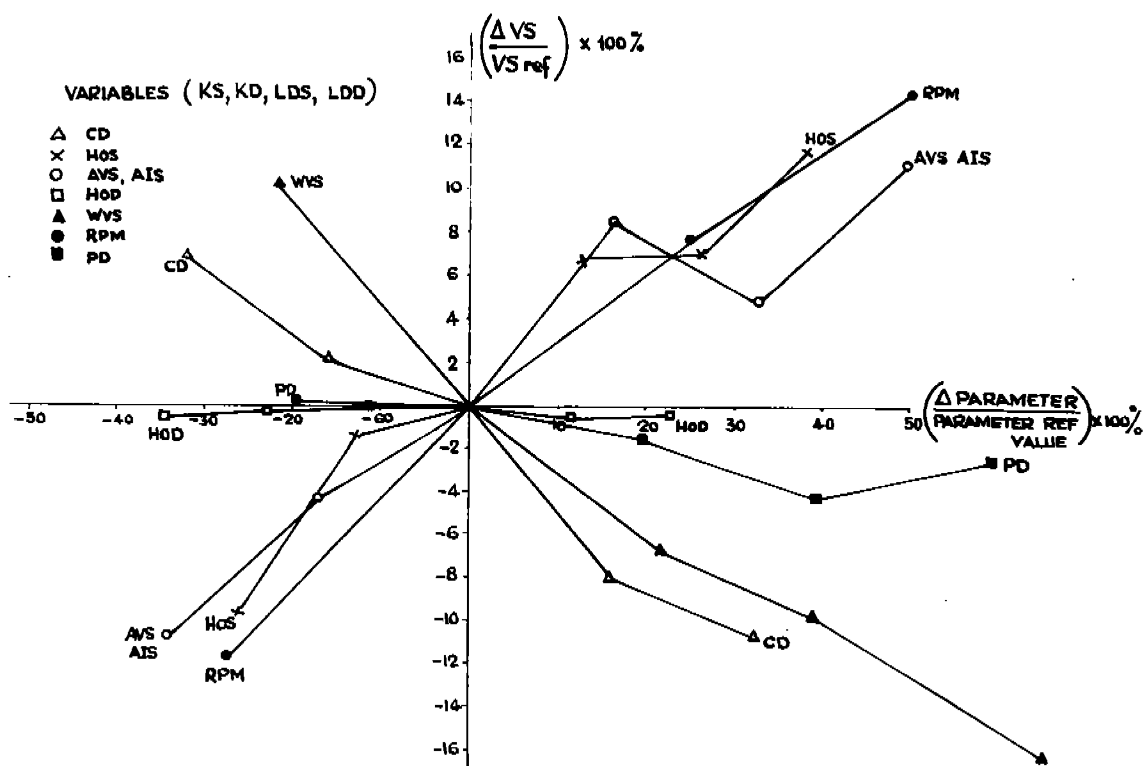

FIG. 6. THE RELATIVE CHANGE IN THE OPTIMISED VALUE OF SUCTION VALVE PLATE IMPACT VELOCITY AGAINST RELATIVE CHANGES IN OTHER PARAMETERS.