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A NEW VALVE DYNAMICS SIMULATION PROGRAM AND ITS USE FOR THE DESIGN OF VALVES

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ABSTRACT

The paper introduces a new valve dynamics simulation program called KV-DYN. Unlike existing conventional programs KV-DYN uses a flow model taking non-steady valve flow into account. Basic equations have been established on the basis of large-scale model experiments and simulation results have been validated. Two new non-dimensional parameters, characterising a compressor-valve-arrangement, are introduced: Relative spring strength and compressibility related valve late closing number. These allow to overlook the influences of all relevant quantities. Another novelty in KV-DYN is the so-called stability diagram. This enables predictions to be made as to the probable incidence of valve flutter.

BASIC CONCEPTS

The computer simulation program "KV-DYN" calculates the important dynamic processes in a suction or descharge valve. It has been worked out by the author (mechanics and flowtherory) in collaboration with his colleague Heinz Stegbauer (mathematics & programming). KV-DYN is intended for engineers

- who have to design valves for process gas and air compressors
- who have to design reed valves for hermetic refrigeration compressors
- who are concerned with diagnosis and maintenance of big compressors

Models have to be abstracted from real processes to allow engineering like calculations of valve dynamics.

Models for Valve Plate Movement and for Valve Flow

The following assumptions are used for calculation of valve plate movement:

- valve plate movement is abstracted to one-dimensional translational movement
- Linear spring force with precompression
- Damping force proportionate to plate velocity
- Flow force calculated by a simplified non-steady flow model as a function of valve exit velocity
- Valve plate impacts completely inelastic

The main assumptions for the valve flow model are:

- One-dimensional non-steady flow for gas transport through the valve
- Working fluid in cylinder considered as compressible, fluid transport through the valve calculated with equations for incompressible fluid
- A so-called "gas spring effect" which considers the "piston like acton" of valve plate was found to be important and taken into account
- Constant pressure in valve plenum chamber

- Constant values for flow and force coefficient, independent of lift
- Isentropic compression and expansion of ideal gas in cylinder

Equations are based on experiments with large-scale models.

The non-steady flow model considers an inertia effect for the gas mass in valve channels and work exchange between valve plate and gas. While simple arithmetic equations tie velocity and pressure difference in steady state flow models, a differential equation results for the used non-steady flow model.

Besides this "main" flow model a special flow model is used for small lifts (typically up to 0.15 mm), which considers friction flow in a narrow gap. Runge-Kutta methods are used to solve the system of differential equations.

NEW PARAMETERS CHARACTERISING A VALVE-COMPRESSOR-ARRANGEMENT

Some, to the knowledge of the author new parameters and diagrams are calculated by KV-DYN prior to numerical integration. These are very useful for the valve designer. Judging them the designer may change input data more systematically.

Equilibrium Curve $X_G(\varphi)$

Let us consider a given compressor-valve-arrangement having a certain compressor speed. Furthermore let us suppose the working fluid is an incompressible gas (like a liquid). The same quantity of fluid volume displaced by the piston in a certain time span has to pass the valve, acting against the springs, thus producing a certain lift X, pressure difference ΔP and valve exit velocity W_2. At this stage we omit superimposed flutter phenomena. The valve lift-crank angle curve originating from this idea is called **equilibrium curve.** To approach this curve to the needs of a valve designer, we start it at the opening c.a. φ_o (calculated from pressure ratio) and "cut" its head –if necessary– by the maximum lift X_{max} given by the lift limiter.

The equilibrium curve simply is calculated by putting equal quasi-steady flow force and spring force. Valve plate mass inertia force is found to be negligible for calculating equilibrium curve. **The equilibrium curve simply reflects the basic relations between piston displacement, gas density, strength of springs and valve geometry for a given compressor-valve arrangement.** One could imagine that measured or simulated lift-c.a. curves may be assumed composed of an equilibrium curve and superimposed flutter oscillations. Fig. 1 shows KV-DYN print outs of valve lift-c.a. curves for 3 different speeds (equilibrium curve: dashed; numerical simulation: full line). The higher the speed, the higher the X_G-maximum $X_{G,max}$

Relative Spring Strength Φ

This is defined as follows

$$\Phi = \frac{X_{max}}{X_{G,max}}$$

Φ characterises by a simple number the whole compressor-valve-arrangement with respect to spring strength. A typical value for nominal condition is: $\Phi = 0.75$; see Fig . 1. Spring selection may start with Φ.

Compressibility related Valve Late Closing Number K

Compressor designs with relative low values of effective valve flow area result in the so-called compressibility valve late closing. Mainly suction valves are concerned. The phenomenon depends not only on effective flow area but also on mean Mach number and on spring strength. All decisive parameters are combined to form K. A complete theory of late closing, which throws fresh light on this complex phenomenon, is given in the book [1]. Fig. 2 indicates the relation between mean late closing c.a. span and K. $K < 0.07$ should be aimed at.

Stability Diagram

This diagram indicates to the valve designer if and to which extent (for a given compressor-valve-arrangement) energy is transferred from gas flow to valve plate. thus increasing flutter and impact velocities or if kinetic energy is sucked out from the valve plate thus damping its flutter motion. Working frequently with this diagram teaches to the valve designer which parameter constellations are favourable. This is not the place for a detailed discussion of the stability diagram.

RESULTS OF NUMERICAL SIMULATION: DIAGRAMS OF VALVE DYNAMICS

The program prints out the following 3 graphs one underneath the other

- valve plate lift $X(\varphi)$
- exit velocity $W_2(\varphi)$
- pressure difference cylinder - plenum chamber $\Delta P(\varphi)$

The valve plate lift diagram also includes the equilibrium curve (dotted line). By the way of Fig. 3 we discuss the 3 diagrams.

Valve Lift Diagram $X(\varphi)$

At point 1 the valve plate impacts on the limiter with 2.5 m/s. At 2 the plate starts to close. The equilibrium curve, which also represents the movement of a massless plate, starts a little bit earlier to the closing movement. The bigger the compressibility late closing number K, the more delayed the real closing movement starts. The valve lift diagram shows clearly, that the plate movement could be regarded as an oscillation superimposed to the equilibrium curve. Under high compressibility late closing conditions the lift curve is shifted to the right while the equilibrium curve remains unchanged as it is calculated under incompressible gas conditions. The "rebound" after the first closing impact is not caused by elastic forces but by the remaining pressure difference in cylinder!

Exit Velocity $W_2(\varphi)$

The velocity spike just beneath point 1 is a result of non steady flow. Under certain conditions this spike transforms to a real acoustic phenomenon following the opening process.

At point 3 the plate reaches a lift of 15 % of the width of the sealing rim and changes over from the main flow model to the model for small gaps: friction reduces the flow velocity. Just before we find another velocity spike: the fast approaching valve plate transfers energy to the flow thus producing the spike.

The main benefit coming from the velocity graph is the following: it shows clearly if back flow near the closing point takes place or not.

Fig. 3 indicates that this is not the case though we have a rebound.

Pressure Difference $\Delta P(\varphi)$

As the program assumes constant pressure in plenum, ΔP is the changing pressure in cylinder. Under certain conditions the opening process of the valve plate is accompanied by a pronounced acoustic phenomenon, Fig. 4 gives an example, frequency about 500 Hz . The valve plate of course can not follow these quick changes. Fig. 4 demonstrates the capability of KV-DYN.

Comparisons of Numerical Results with Experiments

Valve plate lift measurements have been carried out at a suction valve of a big air compressor (piston Ø 320 mm) at the Technical University of Dresden/Germany. I am indebted to Dr. Peter ZOSEL, who let me some results and input data for KV-DYN. For comparisons it is advantageous to choose results with some oscillations rather than "ideal" diagrams. Fig. 5 shows such experimental results and the related simulation results. The equilibrium curve in the experimental diagram is added by hand. Comparisons of Φ could be used to filter out valve effective flow area from measured lift curves.

DISCUSSION OF SOME SPECIAL SIMULATION RESULTS

Fig. 6 shows results for a suction valve of a hermetic compressor (R134a). There is some late closing (about 15^0 c.a. in accordance with K value). Basic data are: piston dia 23 mm; stroke 18 mm; 2950/min; eff. flow area 12 mm^2 : suction pressure 1 bar. Impact velocities are calculated to to +2, - 0.5 m/s. A simulation neglecting non-steady effects looks similar but results in a considerably higher impact level: +2.3; - 0.7 m/s.

Fig. 7 gives an idea of a new valve concept. worked out with KV-DYN, the so-called FL-Valve (apl. for an int. pat.): Instead of a lift limiter strong springs intercept the valve plate when opening. Under normal conditions heavy flutter would result and destroy the plate. Using an inertia effect of the gas in elongated channels damps out flutter. Only simulations taking non-steady flow into account can model these processes. The FL-valve reduces the impact loads to a fraction thus promising high reliability and long valve life. Pioneering experiments have been carried out at Technical University of Dresden using the compressor shown in Fig. 5. They where positive and confirmed KV-DYN simulations.

CONCLUSIONS

- Introduction of the quantities "relative spring strength" and "compressibility related valve late closing number" allows a more systematic valve design.
- KV-DYN, a new computer simulation program for valve dynamics taking non-steady flow into account, gives a better understanding of the dynamic processes in the valve. KV-DYN is a valuable tool for the valve designer.
- KV-DYN discloses a new valve concept: the so-called FL-valve, promising high reliability and superior valve life.

REFERENCES

[1] Böswirth, L. : Flow and Valve Plate Dynamics in Compressor Valves. In German language. Published by the Author 1994. Reprint 1996. 400 p. Price: US $ 135.- (hardcover US $ 155.-) + mailing cost. To obtain a copy: write (or fax) to the Author: Argentinierstraße 28/7; A-1040 Vienna/Austria; (FAX: 0043-1-9826562)

[2] KV-DYN, © Böswirth & Stegbauer. To get more information, write to the address in [1].

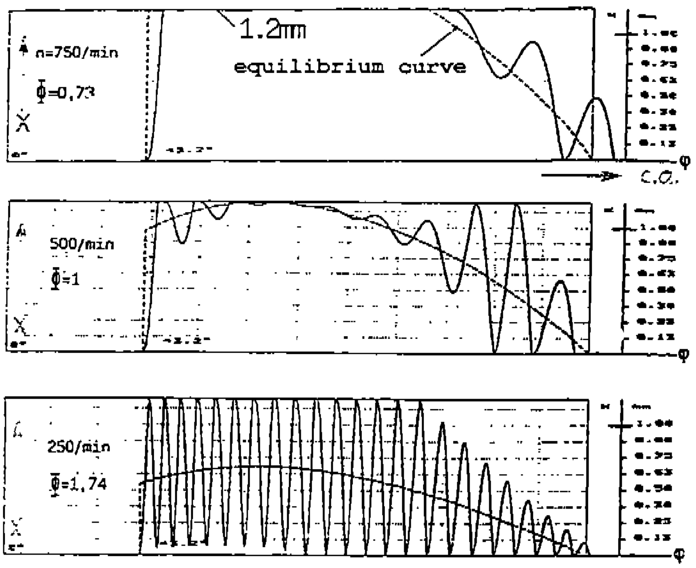

Fig. 1 Comparison of valve plate dynamics for different compressor speeds. Nominal speed: 750/min. The lower the speed, the lower the maximum of the equilibrium curve and the more flutter oscillations occur.

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Valve Dynamics Diagrams
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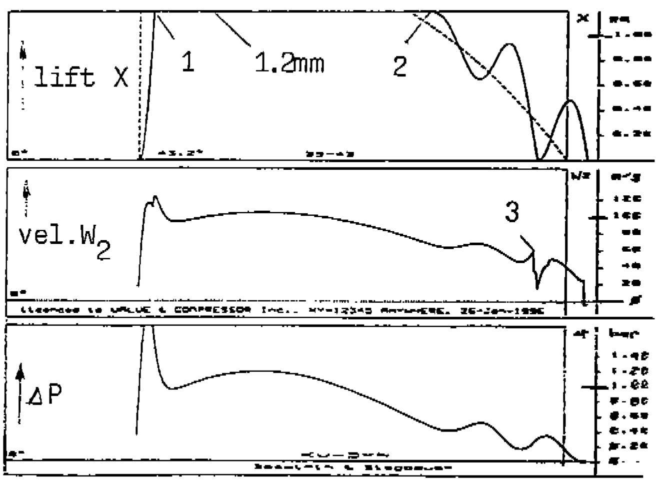

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C A L C U L A T E D   G E N E R A L   D A T A :

   piston mean speed ...............................        3.00 m/s
   valve mean Mach number ..........................        0.16
   theor.max.rel. valve pressure loss (Qi-value)           0.048
   spring related lower speed limit ..............          502 1/min
   relative spring strength .......................         0.73
   mean impact velocity on seat plate ............         0.164 m/s
   compressibility related valve late closing nq.          0.015
   valve plate spring mass natural frequency fo .          125.3 Hz
   acoust. natural frequency related to fo  t.d.c           7.9
                                            b.d.c           2.7

PARAMETERS RESULTING FROM INTEGRATION PROCEDURE:

   valve plate impact velocities in m/s (+ limiter, - seat)
      2.5  -0.6  -0.8

   valve loss work ................................       249.98 Nm
      ( 3.01% of theor. isentropic cycle work)
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Fig. 3 Simulation results for the suction valve of a process gas compressor

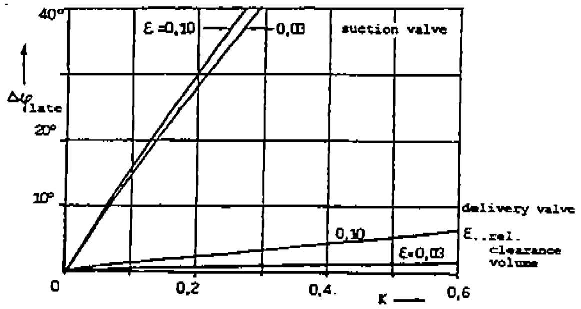

Fig. 2 Relation for compressibility related late closing

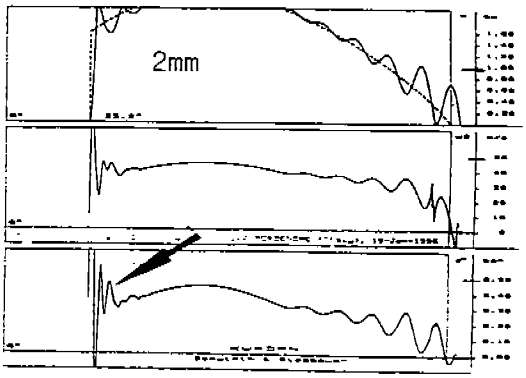

Fig. 4 Special example indicating that KV-DYN can model acoustic phenomena following the valve opening process

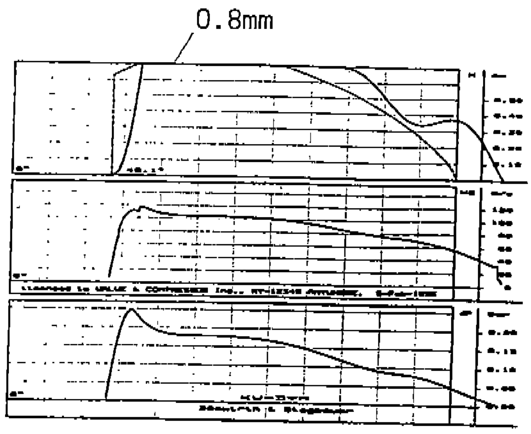

Fig. 6 Simulation results for a hermetic refrigeration compressor showing valve late closing.

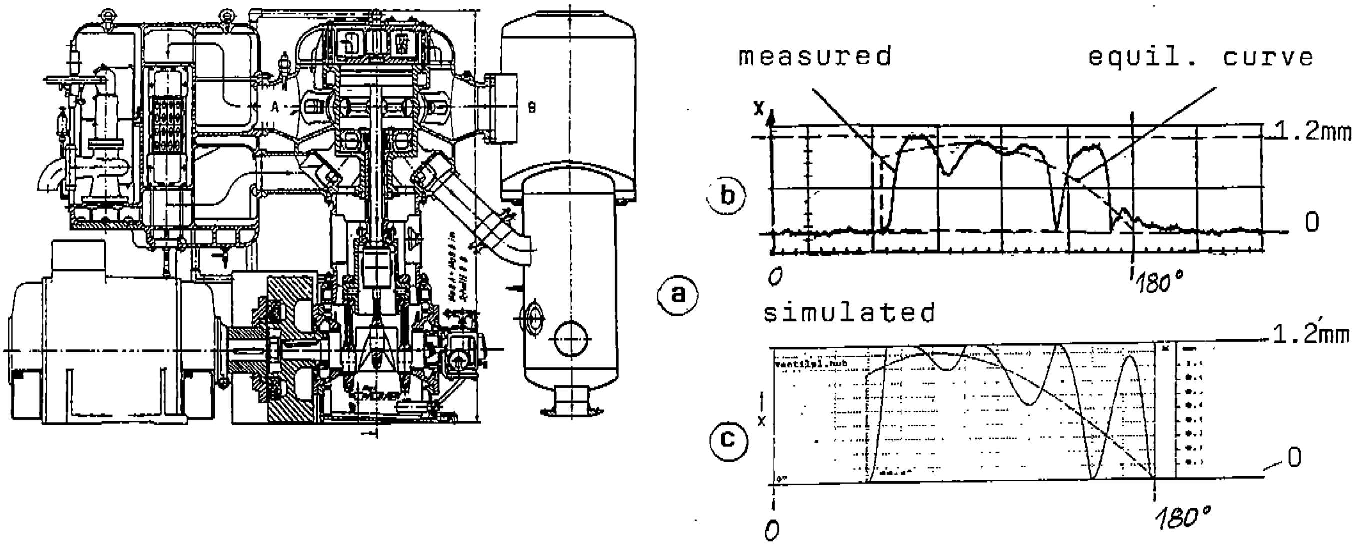

Fig. 5 Valve plate lift measurements and comparison with simulation results. **a** Two stage air compressor in the Lab of T. U. Dresden. **b** Lift measurements at suction valve, 2nd stage, done by P. ZOSEL; equilibrium curve added by hand; speed: 534/min. **c** KV-DYN simulation results

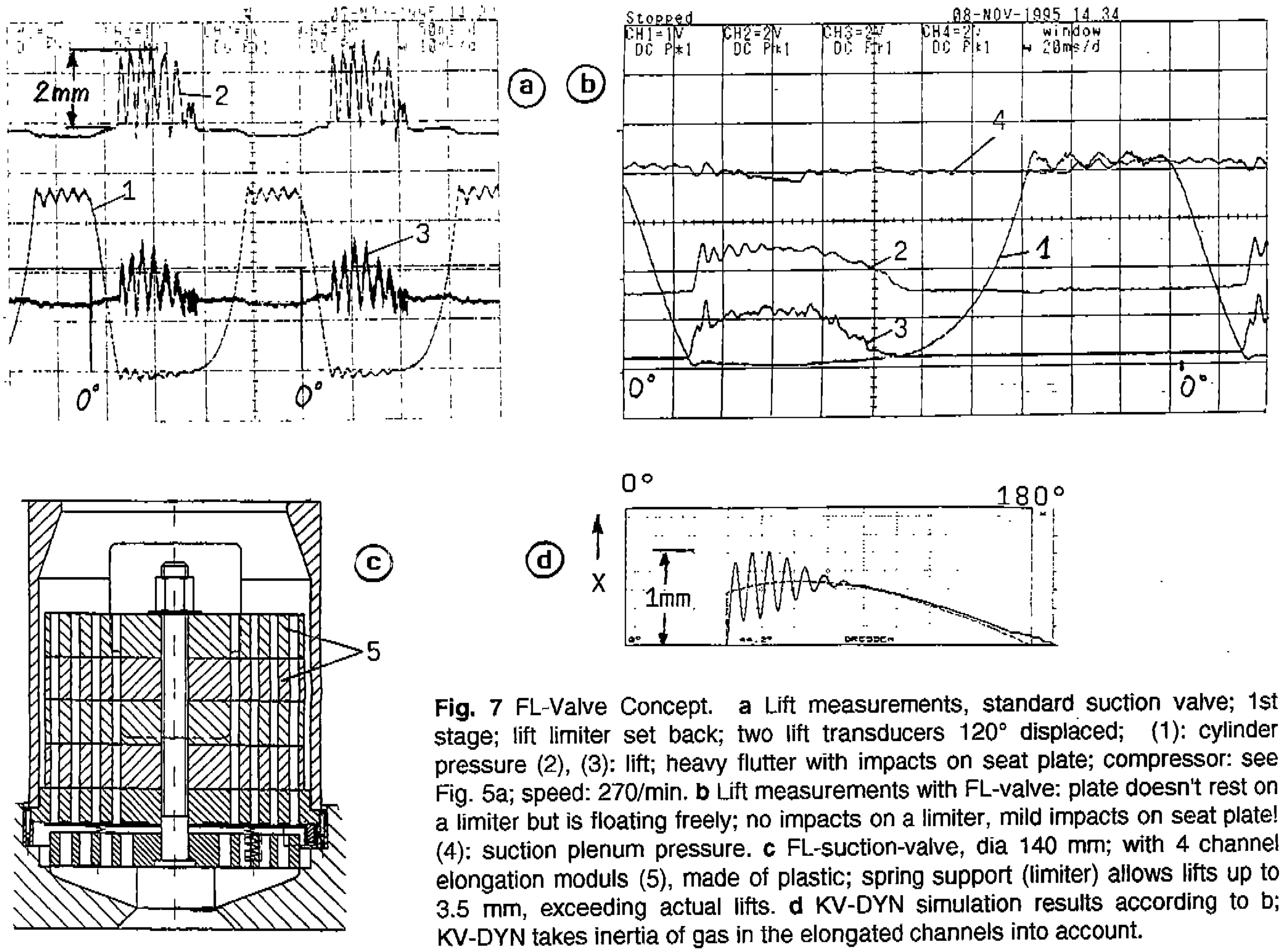

Fig. 7 FL-Valve Concept. **a** Lift measurements, standard suction valve; 1st stage; lift limiter set back; two lift transducers 120° displaced; (1): cylinder pressure (2), (3): lift; heavy flutter with impacts on seat plate; compressor: see Fig. 5a; speed: 270/min. **b** Lift measurements with FL-valve: plate doesn't rest on a limiter but is floating freely; no impacts on a limiter, mild impacts on seat plate! (4): suction plenum pressure. **c** FL-suction-valve, dia 140 mm; with 4 channel elongation moduls (5), made of plastic; spring support (limiter) allows lifts up to 3.5 mm, exceeding actual lifts. **d** KV-DYN simulation results according to b; KV-DYN takes inertia of gas in the elongated channels into account.