High Temperature Calibration and Linearization of a Inductive Valve Displacement Transducer

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HIGH TEMPERATURE CALIBRATION AND LINEARIZATION
OF AN INDUCTIVE VALVE DISPLACEMENT TRANSDUCER.

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GENERAL

Dealing with reciprocal reed valve compressors, measurements on the valve system are inevitable.

The use of inductive displacement transducers is not claimed novel, but so far, little or no information has been published on the high temperature calibration technique.

This paper presents a practical solution to the calibration problem and, in turn, a useful formulae approximating the calibration curve is gained.

The author intends to stay practical, thereby sacrificing a more correct, but elaborated mathematical solution on the magnetic circuit calculation on behalf of a less accurate, slide-rule adaptable solution, immediately dealable in the laboratory.

INTRODUCTION TO THE MEASUREMENT PRINCIPLE

The displacement transducer, a solenoid (Ill. 1), must be built into the piston compressor in such a way that the reed valve can be 'seen' (Ill. 2) but without introducing interference to the valve function, of course. That's an art!

Ill. 1 shows two prototype solenoids.
The dimensions (in mm) have been reduced app. 30% for the types now in use.

Ill. 2 (opposite) shows the displacement transducer built into the valve plate.

Having succeeded, like fighting the mythological dragon, the next problem arises:

How to calibrate the displacement transducer at high temperatures?

Low temperatures give no problems simply by using a micrometer screw gage.

Neglecting the temperature drift of the solenoid, one rarely surpasses this point.

What are the requirements like:

1. Simple calibration procedure
2. Evaluation of the valve deflection during the experiment time in laboratory.
3. Repeatability and long time reliability.
4. Linearization of the oscilloscope picture for further investigations.
To solve req. l-4 let's attempt to imagine what the displacement transducer (the solenoid built into the valve plate and the reed valve) looks like as seen by the electronic 'black box' connected to the wire-end terminals.

It will see an impedance \( Z \) composed by an inductance \( L \) related to the magnetic reluctance of the surroundings, and a resistance \( R \) as a measure of the system's power loss, connected (conveniently chosen) in series.

The presence of the reed valve acts like a lossy, one-turn secondary coil in a transformer. As the airgap varies, the primary inductance and resistance is influenced, leaving to the individual the choice of which parameter, \( L \) or \( R \), to be used as a measure of the valve displacement.

Sound's simple? Actually, the selection of the parameter is implied by the aforementioned electronic 'black box' employed.

Therefore, let us devote some time to

**THE ELECTRONIC EQUIPMENT**

Basically, it's convenient to divide the electronic equipment in use into two categories based on their working principles.

Incorporating the displacement transducer as a part of a high frequency oscillator whose amplitude depends on the tank circuit loss, one achieves a simple, highly sensitive system mainly suffering from an inadequate long-time stability due to the regeneration principle and overload tendency giving a limited operation range. Acquiring information of the valve's extreme outer position, one will have difficulties in attaining a meaningful signal when the valve touches the displacement transducer.

Admittedly, the equipment is inexpensive and many experiments based on this system have been carried out successfully.

The second system of interest is based on the well-known, highly reliable bridge measurement techniques offering reproducible results.

A strain gage carrier amplifier is well suited for valve displacement measurements simply by changing the Wheatstone-bridge into a Maxwell- or Anderson-bridge (Litt. 1) taking the advantage of their frequency independence (thereby maintaining bridge balance over the whole frequency band of interest) and still using the built-in balance controls. The outside modification is evident from fig. 1.

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**Fig. 1** Simplified Circuit Diagram of Valve Displacement Bridge System.
The amplification of the carrier amplifier is adjusted by means of the built-in strain gage calibration standard, thereby leaving the repeatability and long-time stability to a high precision resistor.

The domination of the inductive and resistive part of the displacement transducer is adjusted by means of the PHASE control.

Having the electronic equipment properly adjusted, the solenoid built into the valve plate and an oscilloscope, including a camera, connected to the system, we can now proceed with

**THE HIGH TEMPERATURE CALIBRATION PROCEDURE**

This procedure is based on the following two main points:

1. a Temporarily removing the reed valve enables the displacement transducer to 'see' the top of the piston. Fig. 2
   b The smallest possible airgap between the piston top and the valve surface is known.

2. The DC-resistance of the solenoid is proportional to the temperature.

Now, simply by switching on the main supply to the compressor, checking the coil resistance, and at the desired temperature photographing the oscilloscope screen, the high temperature calibration curve is (almost) achieved. See fig. 3

![Fig. 3](image)

Piston movement as registrated by three individual displacement transducers. Also shown are the TDC marker and the 1 ms calibration signal.

![Fig. 2](image)

High Temperature Displacement Transducer Calibration Setup
The calibration picture (Fig. 3), the oscilloscope trace speed, the revolution frequency and the well-known compressor block geometry enables us to calculate the piston position related to time bearing in mind the absence of valves otherwise causing a distortion of the compressor motor speed.

The result is shown in Fig. 4.

Note: The ordinate values are arbitrarily chosen, e.g., 'mikrovolt per volt', a measure of bridge imbalance related to the bridge supply voltage.

It's evident that the calibration curves are incomplete due to the airgap between the piston and the valve plate surface. The reed valve on the other hand will inevitably touch the valve plate during actual work. How do we cut off the dragon's last head?

Can we find a solution to this extrapolation problem?

If we substitute the actual flux line propagation, Fig. 8, in the way shown in Fig. 9, maintaining the requirement

\[ \int N = \oint H \, d\psi \]

we are able to calculate the reluctance \( \Phi \) of the magnetic circuit leading to the inductance of the transducer:

\[ L = \frac{N^2}{R} \]

As deduced in appendix I this procedure gives the solution:

\[ L(\psi) = L_0 \left( \frac{1 + \cosh[\alpha(x_0 + x_0)]]}{1 + \beta \cosh[\alpha(x_0 + x_0)]} \right) \]

where \( \beta = \frac{R}{N} = \frac{\alpha}{\nu} \)

Incorporating the relative inductance variation \( \frac{\Delta L}{L_0} \) due to the valve displacement, we can express the actual displacement by

\[ x_v + x_0 = \frac{\Delta L}{L_0} \ln \left( \frac{2 \frac{L_0}{L} + 1}{2 \frac{L_v}{L} + 1} \right) \]

where \( \lim_{L_v \to \infty} \psi = 1 \)
Experiments have shown that the sensitivity of the displacement transducer heavily depends on the way the solenoid is positioned into the valve plate. Uniformity is unattainable, and for this reason the sensitivity constant $\alpha$ and the distance $x_0$ from the magnetic source to the valve plate surface were deducted imperically from the piston movement picture.

We have found formulae (4) very handy as it requires only two calibration points for the calculation of $\alpha$ and $x_0$; this enables us, if desired, to draw the complete calibration curve.

During the time of experiment you are now able to find the valve deflection at each point of interest solely by manipulating a slide rule.

Further investigations according to req.4 the deflection picture (Fig.6) must be undertaken.

**LINEARIZATION PROCEDURE**

Although only two points will do as mentioned previously, we have found convenience by involving a digital computer to gain $\alpha$ and $x_0$ by means of least-squares-residual method. Furthermore, information on the oscilloscope trace speed, the calibration settings, the revolution frequency, the correction curve to compensate the distortion of the oscilloscope-to-digital system etc. are also given as input to the computer. It is now a simple task to linearize the deflection picture employing formulae (4).

![Fig. 5 Linearized deflection patterns as gained from the computer.](image)

*Note: The illustrations are not comparable.*

**PERFORMANCE**

Using the bridge system a valve deflection of 0-3 mm may be measured. The equipment optimal adjusted piston movements up to 7 mm have been detected, sacrificing the temperature stability. The accuracy mostly depend on the measurement of the airgap between the piston top and the valve plate surface. Values around 3-5 % are common but depends, due to the exponential function involved, on the actual distance.

The system noise is equivalent of app. 1 $\mu$m at 0.25 mm distance with 5 kHz bandwidth.

![Fig. 6 Oscilloscope picture showing the TDC and BDC marker signal plus three valve deflection patterns of the suction valve.](image)

![Fig. 7 TDC marker signal and piston movement registrated by the displacement transducer.](image)

$Y = 10 \mu$m/div

$X = 1.5$ degr./div
CONCLUSIVE COMMENTS

To confirm the reliability of the calibration procedure outlined in this paper various tests have been undertaken, e.g. comparisons of screw gage versus piston calibration, all passed in favor to the latter method.

As predicted (Appendix I) the dissimilarities of the magnetic properties of the piston and reed valve have negligible effect on the sensitivity of the inductive displacement transducer.

(Compensation, if desired, is possible through adjustment of the PHASE control).

Although the temperature drift of the transducer going from room temperature up to the working point of the compressor can not be neglected (otherwise obsoleting this paper!) in most cases only one calibration picture has been found necessary within the normal temperature range of the compressor.

The work outlined in the present paper has been carried out as a part of a development program at The Research Dept., Compressor Group, DANFOSS, Denmark.

LITERATURE

Scutinising the literature available very little information on the subject have been found.

2. P. Silvester: Modern Electromagnetic Fields, Prentice Hall

APPENDIX

To obtain the extrapolation formulae three actual fluxline propagation has been converted into squares as shown below.

Fig.8

Actual Propagation

Fig.9

Converted Propagation

The formal solution based on the actual flux line propagation suffers from a disadvantage common to many formulae: it frequently leads to integrations e.g. Elliptic Integrals difficult to carry out.

Converting the actual propagation into squares, a very simple solution is obtained.
The magnetic circuit theory (litt.2) states

$$ \mathcal{F} = \phi \sum R_k = \phi \mathcal{H} dl $$

1. \( N \) = Ampere-turns
2. \( \mathcal{F} \) = magnetic force
3. \( \phi \) = total flux
4. \( R \) = reluctance

The inductance of the displacement transducer \( L \) is related to the reluctance by

$$ L = \frac{N^2}{R} $$

The reluctance is inverse proportional to the permeability as seen by

$$ \phi = \int_B dA $$
$$ = \mu \phi H dl $$
$$ = \mu \mathcal{F} \frac{dA}{dl} $$

$$ R = \frac{1}{k \mu} \quad k = \frac{dA}{dl} $$

The converted flux line propagation (fig.9) gives:

$$ \frac{dI}{dx} = -R \phi $$

$$ \frac{d\phi}{dx} = -R \frac{dI}{dx} $$

Defining

$$ \alpha = \sqrt{R \lambda} $$
$$ \lambda = \frac{1}{k \mu} $$

This procedure leads to the differential second-order equation:

$$ \frac{d^2I}{dx^2} = -R \frac{d\phi}{dx} = \lambda R \phi $$

$$ \frac{d^2 \phi}{dx^2} - \alpha^2 \phi = 0 $$

having the general solution

$$ \phi = -\frac{1}{\lambda} \left\{ C_1 \sinh [\lambda x] + C_2 \cosh [\lambda x] \right\} $$

$$ I = C_1 \cosh [\lambda x] + C_2 \sinh [\lambda x] $$

\( C_1 \) and \( C_2 \) are determined by the boundary conditions

$$ I(0) = I \cdot N \cdot \mathcal{F} $$
$$ I(x) = R \phi(x) \quad x = x_0 + x $$

leading to

$$ C_1 = \mathcal{F} $$

$$ C_2 = \frac{1}{\lambda} \frac{\mathcal{F} \cdot e^{\lambda x}}{\cosh^2 [\lambda x]} $$

For the transducer we find

$$ F(x) = \mathcal{F} \cosh [\lambda x] + \phi \lambda x \sinh [\lambda x] $$

$$ \phi(x) = \cosh [\lambda x] + \frac{\mathcal{F} \cdot \lambda}{R} \sinh [\lambda x] $$

The reluctance is calculated as

$$ R(x) = \frac{\mathcal{F}(x)}{\phi(x)} $$

$$ R(x) = \alpha - \frac{R_0}{\alpha} + \frac{\tanh [\lambda x]}{1 + \frac{\mathcal{F} \cdot \lambda}{R_0} \tanh [\lambda x]} $$

As

$$ \lim_{x \to \infty} \tanh \alpha = 1 $$

the following eq. is valid

$$ \lim_{x \to \infty} R(x) = \alpha $$

With the reed valve absent the transducer inductance is given by

$$ L_0 = \frac{N^2}{\alpha} $$

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The actual inductance with the valve present at the distance \( x = x_0 + x_v \) is

\[
L(x) = L_0 \left( 1 + \frac{\beta + e^{2x} \tanh [\alpha x]}{1 + \beta e^{2x} \tanh [\alpha x]} \right) \quad \beta = \frac{R_v}{\alpha}
\]

To find the actual deflection of the valve we must derive

The Inverse Formulae

Substituting

\[
\tanh x = \frac{e^{2x} + 1}{e^{2x} - 1}
\]

we find

\[
L(x) = L_0 \left( \frac{\beta + 1}{\beta + e^{2x} + \beta - 1} \right)
\]

or

\[
\frac{L(x)}{L_0} = 1 + \frac{\alpha L}{L_0} = \frac{e^{2x} - \phi}{e^{2x} + \phi}
\]

where

\[
\phi = \frac{\beta - 1}{\beta + 1} = \frac{R_v}{\alpha} - 1 = \frac{k_0 k_v}{\alpha} - 1 = \frac{k_0}{\alpha + 1} k_v + 1
\]

\[
\lim_{x \to -\infty} \phi = \lim_{x \to -\infty} \frac{k_0 - 1}{x + 1} = -1
\]

As the permeability of the valve (and the piston) is much higher than the permeability of the medium in the airgap, the displacement transducer is almost insensitive to the material detected. This has been confirmed by experiments.