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# Pump rod forces due to hydrodynamic effects in piston pumps

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# PUMP ROD FORCES DUE TO HYDRODYNAMIC EFFECTS IN PISTON PUMPS

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## ABSTRACT

A mathematical model has been set up to describe flow and pressure fluctuations in a pump system of a wind pump for single acting piston pumps. With this, hydrodynamic forces acting on the pump rod can be calculated. Hydrodynamic forces make an important contribution to the total pump rod force.

Experiments have been performed on a laboratory version of the so-called Tanzania pump. Different air volumes of the delivery airchamber, different delivery heads and different rotational speeds were chosen to obtain enough information to check the validity of the model.

For the measuring and the elaboration of the measurements, computer programs were developed using a new data acquisition system. This new system operates very satisfactorily and is a relief compared to the old one.
Also a new magneto-inductive flow meter has been installed. However there are still incertanties as to the reliability of this sensor.

Simple analytical expressions using Fourier transform analysis methods were obtained for the pressure and flow fluctuations in the pump system, from which the forces acting on the pump rod can be calculated. Comparison between theoretical and experimental results suggest that the pressure fluctuations are predicted correctly by theory. This is yet not the case in comparing theory and experiment with regards to the flow fluctuations. Apart from the irreliabilty of the flow meter, this could also be due to the complex flow in and out of the airchamber that is not correctly modelled in theory.

There is certainly need for further analysis of the measurements possibly supplemented by a new set of measurements. However,

design rules already can be derived from the results obtained so far. A good sizing of the airchamber in relation to the stroke volume of the pump keeps the pressure fluctuations, and so the fluctuating hydrodynamic forces acting on the pump rod, within bounds.

## CONTENTS

**APPENDICES**

## NOMENCLATURE

| | | |
|---|---|---|
| $A$ | cross-section area | $m^2$ |
| $A_1'$ | cross-section area of the delivery line close to the delivery airchamber | $m^2$ |
| $A_{pr}$ | cross-section area of the pump rod | $m^2$ |
| $a$ | acceleration | $m/s^2$ |
| $B$ | constant | - |
| $B$ | magnetic field flux density | $Wb/m^2=Vs/m^2$ |
| $C$ | flow capacitance | $m^4s^2/kg$ |
| $C_0$ | flow capacitance at $\overline{p}_1$ | $m^4s^2/kg$ |
| $C_0'$ | idem, but with air supply | $m^4s^2/kg$ |
| $D$ | diameter | m |
| Dig | digital value | - |
| $e$ | voltage difference | V |
| $F$ | force | N |
| $F_{hydr}$ | hydrodynamic force | N |
| $f$ | pressure loss coefficient | - |
| $g$ | gravity acceleration | $m/s^2$ |
| $H$ | static pressure height (head) | m |
| $h$ | height of air column in delivery airchamber | m |
| $K$ | "constant" | - |
| $k$ | gas constant | - |
| $L$ | line inertia | $kg/m^4$ |
| $l$ | length | m |
| $m$ | mass | kg |
| $p$ | pressure | $N/m^2$ |
| $\Delta p$ | pressure fluctuation | $N/m^2$ |
| $\Delta p_{max}$ | maximum of the pressure fluctuation | $N/m^2$ |
| $q$ | flow | $m^3/s$ |
| $\Delta q$ | flow fluctuation | $m^3/s$ |
| $R$ | flow resistance | $kg/m^7$ |
| $R$ | half the length of the stroke | m |
| $s$ | stroke | m |
| $T$ | time for one cycle | s |

| | | |
|---|---|---|
| $t$ | time | s |
| $U$ | voltage | V |
| $v$ | velocity | m/s |

| | | |
|---|---|---|
| $\alpha$ | cranck angle | rad |
| $\alpha_{c,s}$ | closure angle of the suction valve | rad |
| $\alpha_{c,p}$ | closure angle of the pison valve | rad |
| $\gamma$ | adiabatic gas constant | - |
| $\nabla$ | volume | $m^3$ |
| $\nabla_s$ | stroke volume | $m^3$ |
| $\eta_{vol}$ | volumetric efficiency | - |
| $\lambda$ | friction coefficient of the pipe flow | - |
| $\omega$ | rotational (angular) speed | rad/s |
| $\omega_0$ | resonance rotational speed | rad/s |
| $\rho$ | density of water | $kg/m^3$ |
| $\sigma$ | standard deviation | |
| $\bar{\sigma}$ | mean standard deviation | |
| $\zeta$ | pressure loss coefficient | - |

<u>subscripts</u>

| | |
|---|---|
| a | airchaimber |
| atm | atmospheric |
| c | pump cylinder |
| d | delivery, delivery line |
| H | due to static head |
| i | denotes delivery or suction |
| L | due to line inertia |
| l | line |
| p | pump, pump cylinder |
| p | piston |
| R | due to flow resonance |
| s | suction, suction line |
| sta | static |
| syst | system |

<u>superscripts</u>

| | |
|---|---|
| $\wedge$ | dimensionless |
| - | mean |

# 1. INTRODUCTION

The CWD (Consultancy Services Wind Energy Developing Countries) is an organization aiming to transfer know-how on wind energy to people, institutes, governments etc. in developing countries. The Wind Energy Group of the Technical University of Eindhoven, partner in the CWD, designs, develops, tests and improves water pumping windmills.

One of the main problems of the CWD in the last years has been the failure of pump rods. Most probably this is caused by fatigue due to fluctuating forces or by very large forces in the pump rod.
The total pump rod force is a complex composition of forces, not all of which are very well understood, especially the hydrodynamic ones.
Information on pumps can be found in e.g. Bianchi et al [1] and Fox and McDonald [2].

One of the aims of my thesis was to make a model to describe these hydrodynamic forces to get a better insight in these forces. This may lead to rules of thumb for designers of piston pumps on what forces they can expect.
Basic ideas for the model were taken from work done by Henk van der Spek [3].

The WEG is in the possession of a pump test rig in its laboratory. However, up to one year ago the measuring system was rather outdated (see [4] and [5] ). The other aim therefore was to improve this measuring system.

First a description of the pump rod forces is given. Then in chapter 3. the model to describe the hydrodynamic pump rod forces is set up and a first order approximation is derived.
In chapter 4. the pump test rig is described.

Thereafter a more detailed description is given of the new measuring system. In this chapter also a brief description is given of a computer program, made to collect and elaborate pump data.
Measurements were performed to check the validity of the model. The results of these measurements are shown in chapter 6.
Finally, in chapter 7., the conclusions on the new measuring system as well as on the model are given.

# 2. DESCRIPTION OF THE PUMP SYSTEM

## 2.1 THE SINGLE ACTING PISTON PUMP

The pump which is mostly used by the CWD is the single acting piston pump. These pumps consist of a piston, a piston valve and a suction valve, a delivery and a suction line and often two airchambers connected to the lines (see par. 2.3).

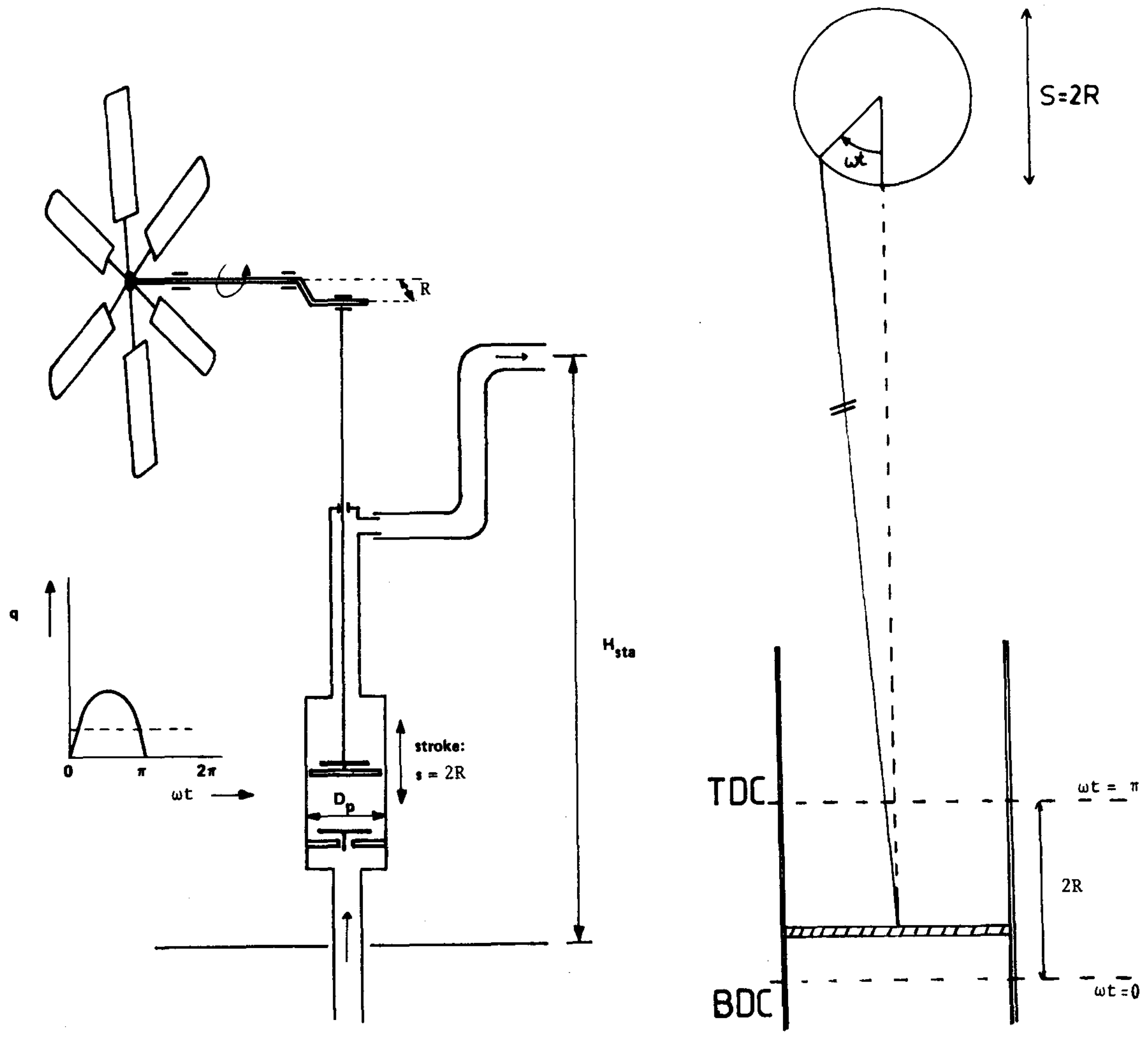


Figure 2.1 Schematic drawing of a piston pump driven by a wind rotor.

A crank-shaft converts the rotational movement of the rotor, or as in our laboratory situation of the motor, into a reciprocating movement of the pumprod and piston (see fig. 2.1).

If the piston moves upwards the pump delivers water: the suction valve is open while the piston valve is closed. The piston sucks the water out of the well and drives it to the outlet of the delivery line. During the downward stroke the piston valve is open and the suction valve is closed. The flow is zero, the piston moves through a stagnant column of water. (See also fig. 2.2.)

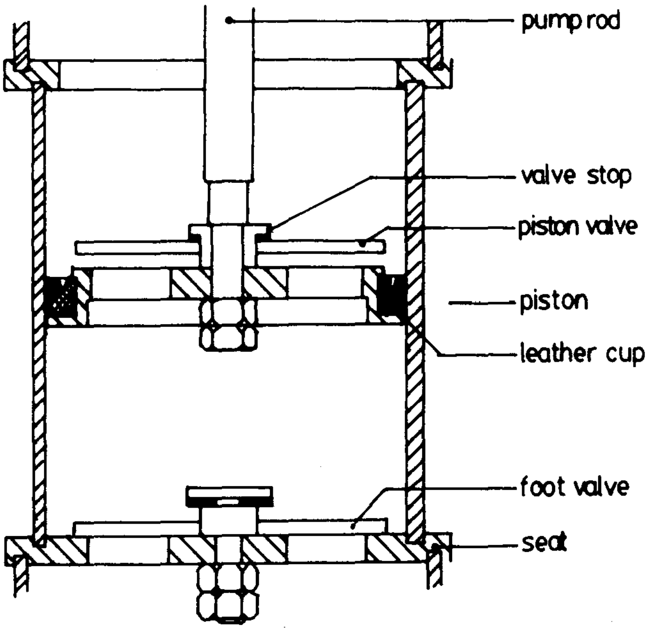


Figure 2.2 Schematic drawing of the piston and the valves. In this situation the piston is moving downwards.

## 2.2 PUMP ROD FORCES

One of the main problems of the pumps is the breaking of pump rods. It may be caused by fatigue due to the fluctuating forces or by the very great forces in the pump rod.

The total pump rod force is a complex composition of forces. These forces can be divided into two main groups: mechanical forces and hydrodynamic forces.

The mechanical forces comprise:

a - the weight of the pump rod and the piston,
b - their acceleration force and
c - the friction force:
    - between piston cup and cylinder wall and
    - between pump rod and cylinder (the sealing).

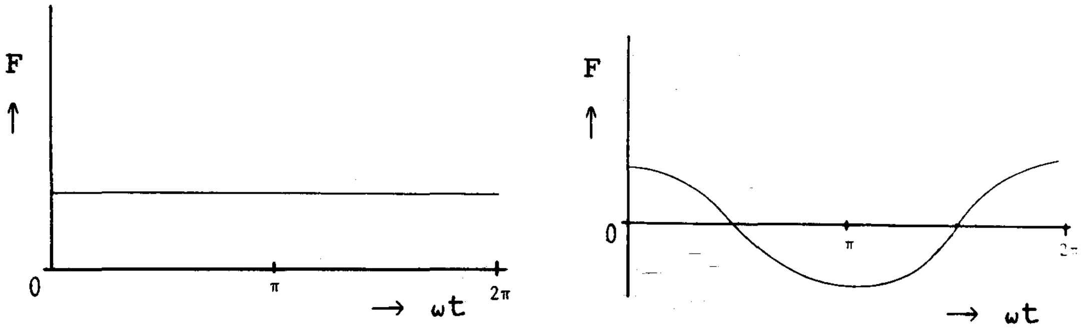
The hydrodynamic forces are related to pressure differences in the pump system. Multiplying these pressure differences by the piston cross-section area gives us the hydrodynamic forces.
The pressure differences are caused by (see also Chapter 3.):

d - the difference in height between the water level of the well or storage tank and the outlet of the delivery line,
e - the acceleration of the water in the pump system and
f - the flow resistance.

Another, very important, hydrodynamic force is

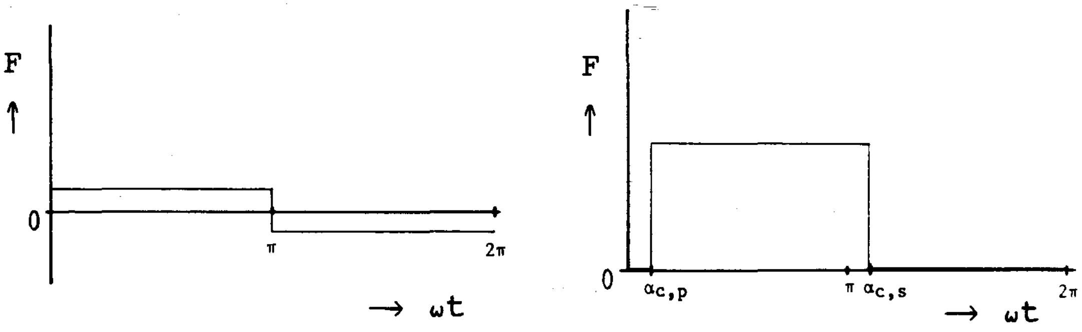
g - the shock force,

caused by valve closure.
This force is related to the delayed closure of the piston valve. The moment the piston valve closes the piston already has a certain velocity in upward direction. This means the water column has to be accelerated from zero to the velocity of the piston in a very short time, resulting in the shock force.



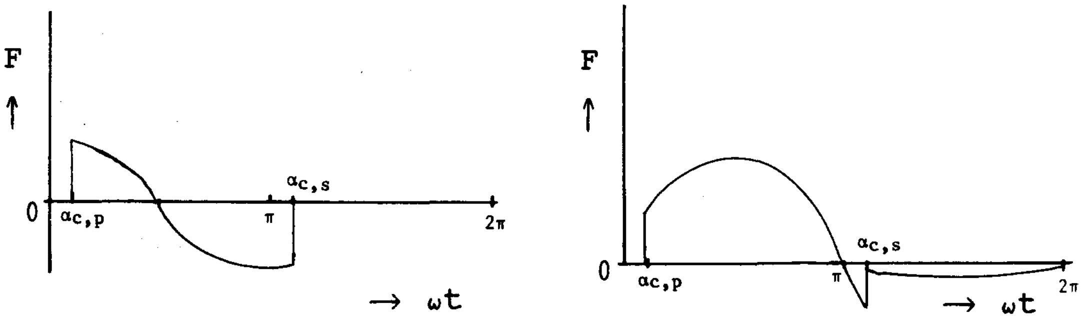
a. Weight of the pump rod.

b. Acceleration of the pump rod.



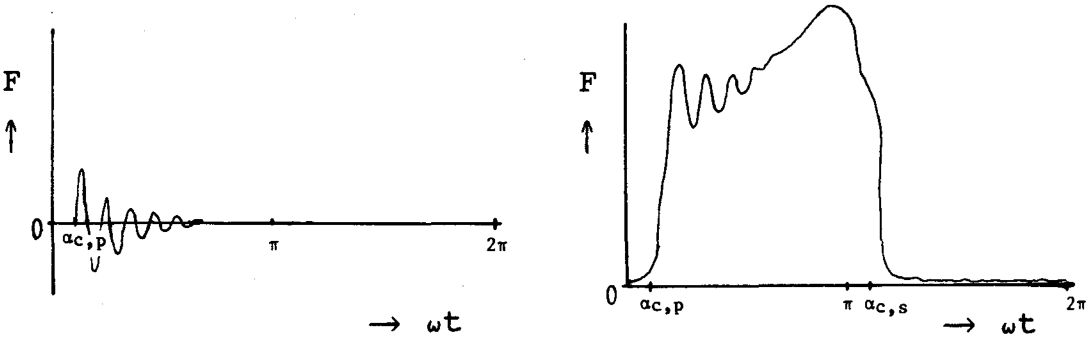
c. Cup friction.

d. Static head.



e. Acceleration of water mass.

f. Flow resistance.



g. Shock force.

h. Total force.

Figure 2.3 The forces a. up to and including g. of page 2-3 and the total force (2.3 h.) as a function of ωt.

More detailed information about the shock force can be found in Snoey [6] and Cleyne [7].

Graphs of these forces a. up to and including g. are given in fig. 2.3. A positive sign of the force means the force is pointing downwards. The angular speed $\omega$ is supposed to be constant during one cycle.

By definition the angle $\omega t$ of the crank-shaft is zero for the lowest position of the piston: the bottom dead center. The angle $\omega t$ equals $\pi$ for the highest position: the top dead center.
At $\omega t=\alpha_{c,p}$ the piston valve closes, at $\omega t=\alpha_{c,s}$ the suction valve closes.

In fig. 2.2 f. the force between $\alpha_{c,s}$ and $\alpha_{c,p}$ is mainly caused by the flow resistance of the piston valve.

The elasticity of the pump rod, its mass and the mass of the water form a (damped) mass-spring system which explains the shape of fig. 2.3 g. As can be seen, the time scale of the shock force is much shorter than the time scale of the other forces. Therefore the shock force can be treated as independent of the other forces.

Forces e. and f. are not independent of each other (see chapter 3.). These forces are responsible for the maximum force in fig. 2.3 h.

## 2.3 AIRCHAMBERS

Piston pumps are often equipped with airchambers to limit the pulsating flow to a more constant flow (see fig. 2.4). This is realized because the airchamber acts as a fluid capacitor. The airchamber temporarily stores water during the upward stroke

(when we consider the delivery side of the pump!) and releases it during the downward stroke.
An ideally operating airchamber would lead to a constant flow in the lines.

Airchambers consist of, for example, cylinders filled with air. They are connected to the lines or built in the pump cylinder as close as possible to the valves to get maximum efficiency of smoothing out the flow.

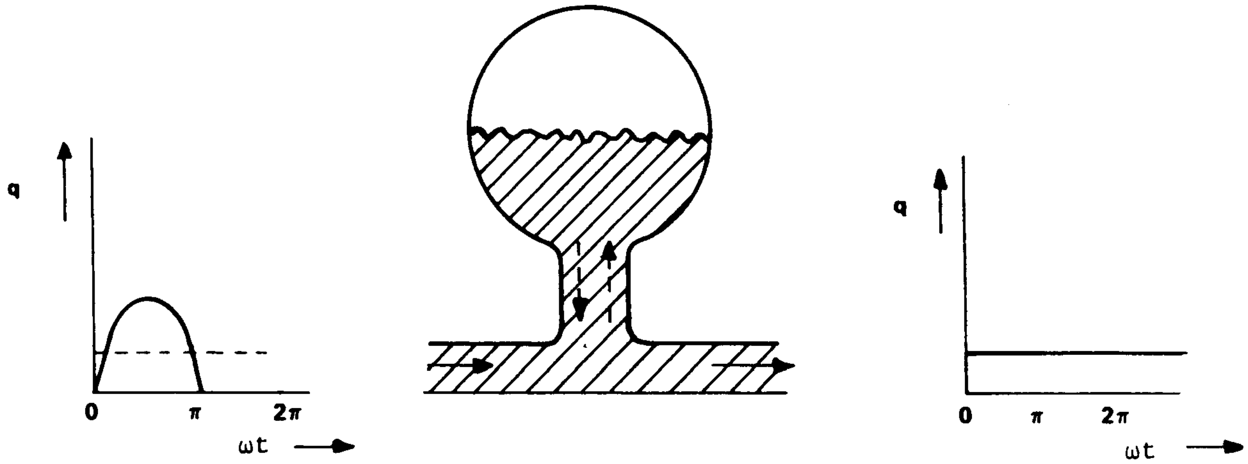


Figure 2.4 The flow before and behind an ideally operating airchamber.

The advantage of smoothing the pulsating flow is the reduction of the acceleration force e. and the shock force g.,which is also a kind of acceleration force. As far as the shock force is concerned, only the mass of water between the airchambers now has to be accelerated.

# 3. A MODEL TO DESCRIBE THE HYDRODYNAMIC FORCES

## 3.1 INTRODUCTION

In this chapter a theoretical model is drafted to describe the flow and pressure fluctuations in the pump system, and particularly the resulting hydrodynamic forces acting on the piston and hence on the pump rod.
Basic ideas were obtained from H.v.d.Spek [3].

The model exists of differential equations in which the flow between the airchambers $q_c$, imposed by the reciprocating movement of the piston, is the starting point for the input signal.

In the second paragraph the hydrodynamic forces are discussed. In paragraph 3.3 the flow through the pump system is described. Then a description of the pressure differences in the pump system is given, followed by a paragraph on the relation between pressure and flow in an airchamber.

With this we finally can set up a model of the pump system expressed in flows, pressures and pump characteristics, which is done in paragraph 3.6.
In the seventh paragraph solutions of the linearised equations of the model are given.

## 3.2 THE HYDRODYNAMIC FORCES

We assume the following conditions to be fulfilled:

- ideal valve behaviour; $\alpha_{c,p}=0$ and $\alpha_{c,s}=\pi$ rad,
- infinite stiffness of the walls,
- infinite stiffness of the pump rod,
- no leakage along the piston and
- length of the pump rod >> the length of the stroke.

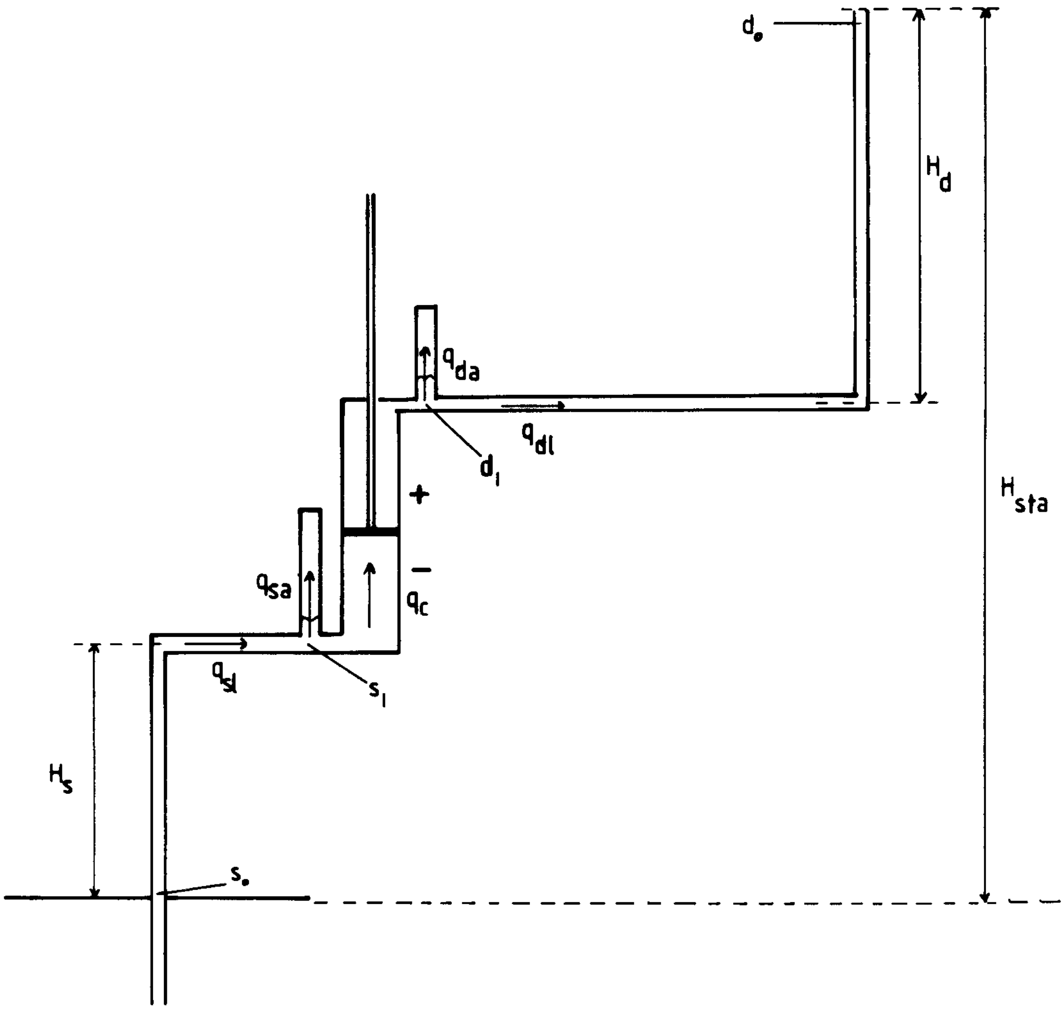


Figure 3.1 Schematic lay-out of a pump system equipped with airchambers. The arrows indicate the direction of the flow through the different parts of the pump system.

At $d_0$ and $s_0$ the pressure is atmospheric.
At $d_1$ and $s_1$ the pressure is $p_{d1}$ and $p_{s1}$ respectively.

We are able to divide the pump system into three independent parts (see also fig. 3.1), which makes the set up of the model much easier:

1 - the suction part: from the water inlet level of the source to the suction airchamber,
2 - the pump cylinder part: between the two airchambers and
3 - the delivery part: from the delivery airchamber to the outlet.

Looking at the piston, we see that there is an excess pressure on the top side of the piston and a reduced pressure at the bottom side. For this reason the pump cylinder part is split up in a "positive" and a "negative" part.

$$p_{p+} - p_{d0} = (p_{p+} - p_{d1}) + (p_{d1} - p_{d0})$$

$$p_{p-} - p_{s0} = (p_{p-} - p_{s1}) + (p_{s1} - p_{s0})$$

$$\overline{\hspace{20em}} \quad -$$

$$p_{p+} - p_{p-} = (p_{c+} - p_{c-}) + (p_{d1} - p_{d0}) - (p_{s1} - p_{s0})$$

in which $(p_{p+} - p_{p-})$ is the total pressure difference over the piston and
$(p_{c+} - p_{c-})$ is defined as $(p_{p+} - p_{d1}) - (p_{p-} - p_{s1})$

The total hydrodynamic force thus becomes

$$F_{hydr} = (p_{p+} - p_{p-}) \cdot A_c \qquad (3.1)$$

in which $A_c$ is the cross-section area of the pump cylinder (or as one wishes, of the piston).

We have to find expressions for $(p_{c+} - p_{c-})$, $(p_{d1} - p_{d0})$ and $(p_{s1} - p_{s0})$. This is done in paragraph 3.4.

All these pressure differences will turn out to be functions of $q_c$, the flow induced by the movement of the piston. Therefore first the flow in the pump system is described.

## 3.3 THE FLOW THROUGH THE PUMP SYSTEM

With the continuity law, we can write for the different parts of the pump system (see also fig. 3.1):

$$q_{sl} - q_{sa} = q_c = q_{dl} + q_{da} \tag{3.2}$$

in which $q_{sl}, q_{dl}$ are the flows through the lines,
$q_{sa}, q_{da}$ are the flows into the airchambers and
$q_c$ is the flow through the pump cylinder.

The velocity of the piston is

$$v_p = \frac{1}{2} s \cdot \omega \sin \omega t$$

with $\omega t = 0$ at the bottom dead center and s being the length of the stroke.
The equation for $q_c$ thus becomes

$$\begin{aligned} q_c &= \frac{1}{2} \cdot A_c s \cdot \omega \sin \omega t \qquad && 0 < \omega t < \pi \\ q_c &= 0 && \pi < \omega t < 2\pi \end{aligned} \tag{3.3}$$

Integrating the flow over one cycle, we find the average flow $\bar{q}_c$

$$\bar{q}_c = \frac{1}{2\pi} \cdot A_c s \cdot \omega = \frac{\omega}{2\pi} \cdot \nabla_s \tag{3.4}$$

in which $\nabla_s$ is the stroke volume of the pump.

In spite of the use of airchambers, the flow in the lines will never be constant. There will always be a fluctuating flow $\Delta q$ on top of the average flow through a line.

$$q_l = \bar{q}_c + \Delta q \tag{3.5}$$

An expression for $q_a$ from (3.2) will be given in paragraph 3.5.

## 3.4 THE PRESSURE DIFFERENCES IN THE PUMP SYSTEM

In our system, pressure differences are caused by

- the static head,
- the flow resistance and
- the acceleration of the water mass.

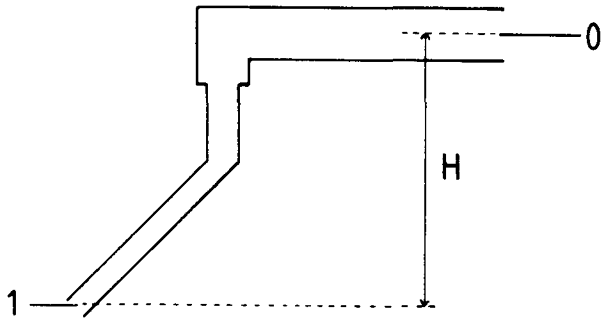


Figure 3.2 A line showing different lengths and diameters.

The pressure difference between the cross-sections 1 and 0 of fig. 3.2 is equal to:

$$p_1 - p_0 = \underbrace{\rho g H}_{\text{static head}} + \underbrace{R \cdot q^2}_{\text{flow resistance}} + \underbrace{L \cdot \dot{q}}_{\text{acceleration}} \tag{3.6}$$

in which R is the flow resistance (in $kg/m^7$) and
L is the line inertia (in $kg/m^4$).

These definitions are explained in Appendix 3A.
Detailed information on this subject can be found in Bianchi et al [1] and many other books on fluid mechanics.

The pressure difference over the piston due to the pressure differences in the pump cylinder part is

$$(p_{c+} - p_{c-}) = \rho g H_c + R_c \cdot q_c{}^2 + L \cdot \dot{q}_c \tag{3.7}$$

We now apply eq. (3.6) to the delivery line and the suction line respectively. In paragraph 3.3 we have found an equation for $q_l$

$$q_l = \bar{q} + \Delta q \tag{3.5}$$

From this equation it follows

$$q_l{}^2 = \bar{q}_c{}^2 + 2 \cdot \bar{q}_c \Delta q + \Delta q^2$$

$$\dot{q}_l = \Delta \dot{q}$$

which turns (3.6) into

$$\begin{aligned} p_{dl} &= \rho g H_d + R_d(\bar{q}_c{}^2 + 2\bar{q}_c \Delta q_d + \Delta q_d{}^2) + L_d \Delta \dot{q}_d + p_{atm} \\ p_{sl} &= -\rho g H_s - R_s(\bar{q}_c{}^2 + 2\bar{q}_c \Delta q_s + \Delta q_s{}^2) - L_s \Delta \dot{q}_s + p_{atm} \end{aligned} \tag{3.8}$$

($p_{d0}$ and $p_{s0}$ both equal the atmospheric pressure, $p_{atm}$)

The pressures can be divided into an average, "constant" part

$$\begin{aligned} \bar{p}_{dl} &= p_{atm} + \rho g H_d + R_d \bar{q}_c{}^2 \\ \bar{p}_{sl} &= p_{atm} + \rho g H_s + R_s \bar{q}_c{}^2 \end{aligned} \tag{3.9}$$

and a fluctuating part

$$\Delta p_{d1} = R_d(2\bar{q}_c \Delta q_d + \Delta q_d^{\,2}) + L_d \Delta \dot{q}_d$$
$$\Delta p_{s1} = -R_s(2\bar{q}_c \Delta q_s + \Delta q_s^{\,2}) - L_s \Delta \dot{q}_s \qquad (3.10)$$

Together with (3.7) the total pressure difference over the piston, $(p_{p+} - p_{p-})$, becomes:

$$p_{p+} - p_{p-} = \rho g H_{sta} + (R_d + R_s)\bar{q}_c^{\,2} + R_c q_c^{\,2} + $$
$$+ R_d(2\bar{q}_c\Delta q_d + \Delta q_d^{\,2}) + R_s(2\bar{q}_c\Delta q_s + \Delta q_s^{\,2}) +$$
$$+ L_c\dot{q}_c + L_d\Delta\dot{q}_d + L_s\Delta\dot{q}_s \qquad (3.11)$$

in which $H_{sta} = H_c + H_d + H_s$.

The first two terms on the right side of eq. (3.11) form the average, "constant" pressure on the piston while the other terms form the fluctuating pressure.

Multiplying (3.11) by $A_c$ gives us the hydrodynamic force acting on the piston (only during the upward stroke !)

$$F_{hydr} = (p_{p+} - p_{p-}) \cdot A_c \qquad (3.1)$$

The only unknown terms in eq. (3.11) are $\Delta q_d$ and $\Delta q_s$. With use of (3.2) and (3.5) we can write

$$\Delta q_d = q_c - \bar{q}_c - q_{da}$$
$$\Delta q_s = q_c - \bar{q}_c + q_{sa} \qquad (3.12)$$

The values of $q_c$ and $q_l$ are linked by the flow into the airchamber which is discussed in the following paragraph.
It will appear that $q_{da}$ and $q_{sa}$ are functions of the pressures $p_{d1}$ and $p_{s1}$ (see par. 3.5).

From here on we use the subscript i to denote d or s. When ± or ∓ is used, the upper sign denotes the delivery part and the lower sign denotes the suction part.

### 3.5 THE PRESSURE AND THE FLOW IN AN AIRCHAMBER

It is possible to express $q_a$, the flow into an airchamber (see also fig. 3.1), in terms of the pressure in that airchamber. For $q_a$ one can write:

$$q_a = - \frac{d\nabla_a}{dt} \tag{3.13}$$

in which $\nabla_a$ is the air volume in the airchamber.

We assume the water to be incompressible.
For the air in the airchamber we take the following relation between volume and pressure:

$$p\nabla^k = \text{constant} \quad \text{or} \quad \nabla = \frac{\text{constant}}{p^{1/k}} \tag{3.14}$$

in which k=1 for isotherm compression and expansion and $k=\gamma=1.4$ for adiabatic compression and expansion.

$$\frac{d\nabla}{dp} = - \frac{1}{k} \cdot \frac{\nabla}{p}$$

We now define the flow capacitance C (in $m^4s^2/kg$):

$$C = - \frac{d\nabla}{dp} = \frac{\nabla}{k \cdot p} \tag{3.15}$$

At a first approximation the pressure loss over the inlet of the airchamber is neglected. This means the pressure $p_a$ of the air in the airchamber is equal to the pressure $p_1$ at the cross-section $d_1$ or $s_1$ and so $\dot{p}_a=\dot{p}_1=\Delta\dot{p}_1$.

With this and definition (3.15), (3.13) becomes

$$q_a = C\cdot\dot{p}_a = C\cdot\Delta\dot{p}_1 \qquad (3.16)$$

We haven't finished with the definition of C yet. In the first place C is varying during one cycle, secondly C is dependent on the mean pressure during that cycle and thirdly C is dependent on the way air is supplied to the airchamber.

For a given rotational speed the constant of (3.14) can be written as $\bar{p}\cdot\bar{\nabla}^k$ and p as $\bar{p}+\Delta p$ ($\Delta p$ can both be positive and negative). Thus with use of a Taylor series:

$$\nabla = \frac{\bar{p}^{1/k}\bar{\nabla}}{(\bar{p}+\Delta p)^{1/k}} = \frac{\bar{\nabla}}{(1+{}^{\Delta p}/_{\bar{p}})^{1/k}}$$

$$\frac{d\nabla}{dp} = -\frac{\bar{\nabla}}{k\cdot\bar{p}}\cdot\frac{1}{(1+{}^{\Delta p}/_{\bar{p}})^{1+1/k}} =$$

$$= -\frac{\bar{\nabla}}{k\cdot\bar{p}}\cdot\left\{1-\frac{1+k}{k}\cdot\frac{\Delta p}{\bar{p}}+\frac{1}{2}\cdot\frac{1+k}{k}\cdot\frac{1+2k}{k}\cdot\left(\frac{\Delta p}{\bar{p}}\right)^2-\cdots\cdots\right\}$$

$$C = \frac{\bar{\nabla}}{k\cdot\bar{p}}\cdot\left\{1-\frac{1+k}{k}\cdot\frac{\Delta p}{\bar{p}}+\frac{1}{2}\cdot\frac{1+k}{k}\cdot\frac{1+2k}{k}\cdot\left(\frac{\Delta p}{\bar{p}}\right)^2-\cdots\cdots\right\} \qquad (3.17)$$

$$C = C_0\cdot\left\{1+\frac{C_1}{C_0}\cdot\frac{\Delta p}{\bar{p}}+\frac{C_2}{C_0}\cdot\left(\frac{\Delta p}{\bar{p}}\right)^2+\cdots\cdots\right\} = C_0\cdot K$$

in which $C_0$ is the flow capacitance at $\bar{p}$ and
K is a abbreviated expression for the function between the brackets of eq. (3.17).

Let us consider the second effect: the influence of the mean pressure. If $\nabla_{atm}$ is the air volume at atmospheric pressure and with slowly increasing rotational speed, we may assume isothermal compression for a constant air mass in the airchamber.

$$p_{atm} \cdot \nabla_{atm} = p_{sta} \cdot \nabla_{sta} = \bar{p} \cdot \bar{\nabla} \tag{3.18}$$

in which $p_{sta}$ is the static pressure ($= p_{atm} \pm \rho g H_i$) and
$\nabla_{sta}$ is the air volume of an airchamber at $p_{sta}$.

$C_0$ thus becomes

$$C_0 = \frac{p_{atm} \cdot \nabla_{atm}}{k \cdot \bar{p}^2} \tag{3.19}$$

$C_0$ is dependent on $\bar{p}_1$ and so on the rotational speed $\omega$. Therefore a new flow capacitance is introduced which is a constant and is related to a certain pump geometry; $C_{syst}$.

$$C_{syst} = \frac{p_{atm} \cdot \nabla_{atm}}{k \cdot p_{sta}^2} \tag{3.20}$$

in which $C_{syst}$ is the specific flow capacitance of the system
at zero flow (capacitance at $p_{sta}$).

With use of eqs. (3.19) and (3.20) two resonance rotational speeds are introduced, $\omega_0 = 1/\sqrt{(LC_0)}$ and $\omega_{syst} = 1/\sqrt{(LC_{syst})}$, the latter being constant.

$$\begin{aligned} \omega_{syst} &= \frac{1}{\sqrt{(LC_{syst})}} = \sqrt{\frac{k}{p_{atm} \cdot \nabla_{atm}}} \cdot p_{sta} \\ \omega_0 &= \frac{1}{\sqrt{(LC_0)}} = \sqrt{\frac{k}{p_{atm} \cdot \nabla_{atm}}} \cdot \bar{p}_1 = \omega_{syst} \cdot \frac{\bar{p}_1}{p_{sta}} \end{aligned} \tag{3.21}$$

We could also think of a system in which air is supplied to the airchamber in order to keep the air volume constant, independent of the rotational speed. This is often used by the CWD in deep well pumps to be assured of an air filled airchamber. Otherwise the airchamber would slowly become empty which leads to enormously increasing pump rod forces.
When air is supplied, $C_0$ can be written as

$$C_0' = \frac{\nabla_{atm}}{k \cdot \bar{p}} \tag{3.21}$$

in which $C_0'$ is the flow capacitance when air is supplied.

From (3.19) and (3.21) we see that both $C_0$ and $C_0'$ are decreasing for increasing $\bar{p}_1$. According to equation (3.9) the average pressure $\bar{p}$ is a function of the average flow $\bar{q}_c$, $\bar{q}_c$ being proportional to the angular velocity $\omega$. Thus the flow capacitances $C_0$ and $C_0'$ become dependent on $\omega$.

$$\begin{aligned} C_0 &= C_{syst} \cdot \frac{p_{sta}^2}{\bar{p}_1^2} = C_{syst} \cdot \frac{1}{(1+\text{const} \cdot \omega^2/\omega_{syst}^2)^2} \\ C_0' &= C_{syst} \cdot \frac{p_{sta}}{p_{atm}} \cdot \frac{p_{sta}}{\bar{p}_1} = C_{syst} \cdot \frac{p_{sta}}{p_{atm}} \cdot \frac{1}{(1+\text{const} \cdot \omega^2/\omega_{syst}^2)} \end{aligned} \tag{3.22}$$

in which const $= (R\nabla_s^2 \cdot \omega_{syst}^2)/(4\pi^2 \cdot p_{sta})$.

$C_0$ and $C_0'$ as a function of the rotational speed squared are shown in fig. 3.3 .

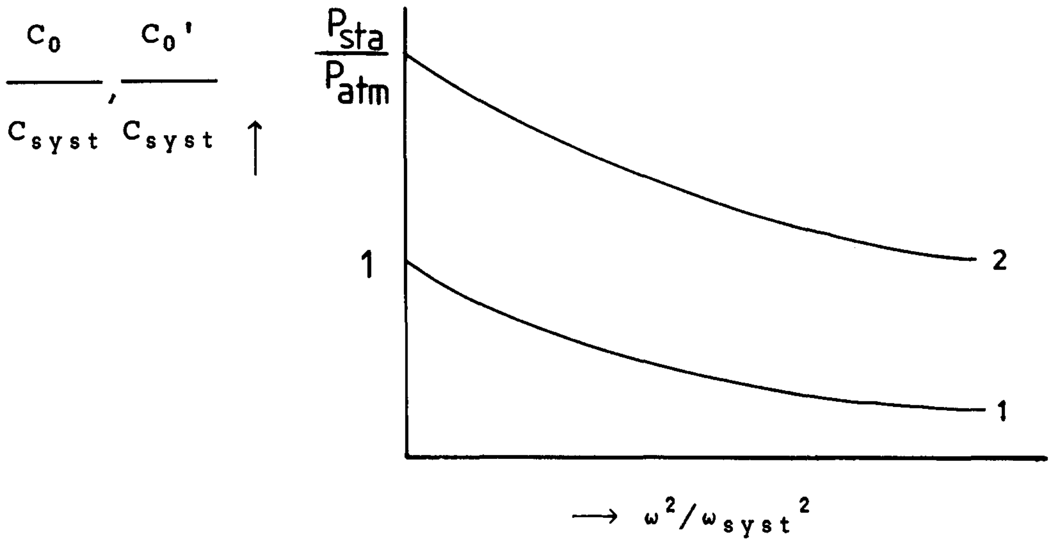


Figure 3.3 The influence of the rotational speed on the flow capacitances $C_0$ and $C_0'$.
1: without air supply ($C_0$), 2: with air supply ($C_0'$)

From fig. 3.3 we see that if air is supplied to the airchamber, the capacitance increases. We therefore may expect both the flow and the pressure fluctuations to decrease.

## 3.6 THE MODEL FOR THE LINE-AIRCHAMBER SYSTEM

### THE BASIC EQUATIONS

It is quite easy to calculate the average pressures $\bar{p}_{i1}$ which are only dependent on the head $H_i$, the flow resistance $R_i$ and the mean flow $\bar{q}_c$. It is far more difficult to calculate the fluctuating flows $\Delta q_i$ and pressures $\Delta p_{i1}$. But it is possible to express them with use of differential equations of second order. Further on some assumptions are made and conditions are drafted, which gives us the possibility to linearise these equations. The equations can then be solved analytically!

We start with the expressions (3.2) and (3.5).

$$q_l = q_c \mp q_a \tag{3.2}$$

$$q_l = \bar{q}_c + \Delta q \tag{3.5}$$

With this the three basic equations become:

$$\boxed{\begin{aligned} \Delta q &= q_c - \bar{q}_c \mp q_a && (3.24) \\ q_a &= C \cdot \Delta \dot{p}_1 && (3.25) \\ \Delta p_1 &= \pm L\Delta \dot{q} \pm R(2\bar{q}_c \Delta q + \Delta q^2) && (3.26) \end{aligned}}$$

## THE MODEL

Rearranging these equations one can write:

$$\Delta q = q_c - \bar{q}_c \mp C_0 K \Delta \dot{p}_1 \tag{3.27}$$

$$\begin{aligned} \Delta q^2 = {} & q_c{}^2 + \bar{q}_c{}^2 + C_0{}^2 K^2 (\Delta \dot{p}_1)^2 - 2q_c\bar{q}_c + \\ & \mp 2q_c C_0 K \Delta \dot{p}_1 \pm 2\bar{q}_c C_0 K \Delta \dot{p}_1 \end{aligned} \tag{3.28}$$

$$\Delta \dot{q} = \dot{q}_c \mp C_0 K \Delta \ddot{p} \mp C_0 K' \cdot (\Delta \dot{p}_1)^2 \tag{3.29}$$

$$\Delta p_1 = \pm L\Delta \dot{q} \pm R(2\bar{q}_c \Delta q + \Delta q^2) \tag{3.30}$$

$$\Delta \dot{p}_1 = \pm L\Delta \ddot{q} \pm R(2\bar{q}_c \Delta \dot{q} + 2\Delta q \Delta \dot{q}) \tag{3.31}$$

K is an abbreviated expression for the function between the brackets of equation (3.17). K' is the derivative of K to $\Delta p_1$.

With (3.31) and (3.27) we can write a differential equation for $\Delta q$ as a function of $q_c$.

$$LC_0K\Delta\ddot{q} + 2RC_0K(\bar{q}_c + \Delta q)\Delta\dot{q} + \Delta q = q_c - \bar{q}_c \qquad (3.32)$$

A similar equation for $\Delta p_1$ is found by substituting (3.27), (3.28) and (3.29) into (3.30).

$$\begin{aligned} LC_0K\Delta\ddot{p}_1 + (LC_0K'\Delta\dot{p}_1 \mp RC_0{}^2K^2\Delta\dot{p}_1 + 2q_cRC_0K)\Delta\dot{p}_1 + \Delta p_1 &= \\ = \pm L\dot{q}_c \mp R\bar{q}_c{}^2 \pm Rq_c{}^2 & \qquad (3.33) \end{aligned}$$

Multiplying (3.27) by $RC_0K$ or $\pm Rq_c$ gives

$$RC_0Kq_c = RC_0K(\bar{q}_c+\Delta q) \pm RC_0{}^2K^2\Delta\dot{p}_1$$

and $$\pm Rq_cq_c = \pm Rq_c(\bar{q}_c+\Delta q) + RC_0Kq_c\Delta\dot{p}_1$$

Again a little calculating is needed to change (3.33) into

$$\begin{aligned} LC_0K\Delta\ddot{p}_1 + (RC_0K(\bar{q}_c+\Delta q) + LC_0K'\Delta\dot{p}_1)\Delta\dot{p}_1 + \Delta p_1 &= \\ = \pm L\dot{q}_c \pm R(\bar{q}_c+\Delta q)q_c \mp R\bar{q}_c{}^2 & \qquad (3.34) \end{aligned}$$

## THE MODEL IN LINEARISED AND DIMENSIONLESS FORM

The equations (3.32) and (3.34) are linear if the following two conditions are fulfilled:

1. $\Delta q << \bar{q}_c$
2. $\Delta p_1 << \bar{p}_1$ $\quad$ ($K=1$ , $K'=0$ (eq. (3.17)) )

Ad 1. With properly operating airchambers one may say $\Delta q \ll \bar{q}_c$. Later on this is proven to be correct for $\omega^2 \gg \omega_0{}^2$.

Ad 2. The ratio between $\Delta p_1$ and $\bar{p}_1$ is dependent on the ratio between the stroke volume and the air volume of an airchamber. This too will be proven later on.

The linearised equations thus become:

$$LC_0\Delta\ddot{q} + 2RC_0\bar{q}_c\Delta\dot{q} + \Delta q = q_c - \bar{q}_c \qquad (3.35)$$

$$LC_0\Delta\ddot{p}_1 + RC_0\bar{q}_c\Delta\dot{p}_1 + \Delta p_1 = \pm L\dot{q}_c \pm R\bar{q}_c(q_c-\bar{q}_c) \qquad (3.36)$$

To make these equations usable for various sizes of pump systems with single acting piston pumps, it is recommandable to write (3.35) and (3.36) in a dimensionless form. The variables q, p and t are made dimensionless in the following way, where the symbol $\wedge$ denotes "dimensionless".

$$\left.\begin{array}{l} \hat{q} = \dfrac{q}{\bar{q}_c}, \quad \dot{\hat{q}} = \dfrac{\dot{q}}{\omega\bar{q}_c}, \quad \ddot{\hat{q}} = \dfrac{\ddot{q}}{\omega^2\bar{q}_c} \\ \hat{p} = \dfrac{p}{\bar{p}_1}, \quad \dot{\hat{p}} = \dfrac{\dot{p}}{\omega\bar{p}_1}, \quad \ddot{\hat{p}} = \dfrac{\ddot{p}}{\omega^2\bar{p}_1} \\ \hat{t} = \omega t \end{array}\right\} \qquad (3.37)$$

The dimensionless form of eqs. (3.35) and (3.36) thus becomes

$$A_2\Delta\ddot{\hat{q}} + 2A_1\Delta\dot{\hat{q}} + A_0\Delta\hat{q} = \hat{q}_c - 1 \qquad (3.38)$$

$$A_2\Delta\ddot{\hat{p}}_1 + A_1\Delta\dot{\hat{p}}_1 + A_0\Delta\hat{p}_1 = \pm B_1\dot{\hat{q}}_c \pm B_0(\hat{q}_c-1) \qquad (3.39)$$

in which the dimensionless quantities are, see eqs. (3.22), (3.23) and (3.4):

$$\left.\begin{aligned}
A_2 &= \omega^2 L C_0 = \frac{\omega^2}{\omega_0{}^2} = \frac{p_{sta}}{\overline{p}_1} \\
A_1 &= \omega R C_0 \overline{q}_c = \frac{\omega^2}{\omega_{syst}{}^2} \cdot \frac{R \cdot \nabla_s}{2\pi \cdot L} \cdot \frac{p_{sta}{}^2}{\overline{p}_1{}^2} \\
A_0 &= 1 \\
B_1 &= \frac{\omega L \overline{q}_c}{\overline{p}_1} = \frac{\omega^2}{\omega_{syst}{}^2} \cdot \frac{L \cdot \omega_{syst} \cdot \nabla_s}{2\pi \cdot \overline{p}_1} \\
B_0 &= \frac{R \overline{q}_c{}^2}{\overline{p}_1} = \frac{B_1 A_1}{A_2} = \frac{\omega^2}{\omega_{syst}{}^2} \cdot \frac{R \cdot \omega_{syst} \cdot \nabla_s{}^2}{4\pi^2 \cdot \overline{p}_1{}^2}
\end{aligned}\right\} \qquad (3.40)$$

with $\overline{p}_1 = p_{sta} + \frac{R \cdot \nabla_s{}^2}{4\pi^2} \cdot \omega syst \cdot \frac{\omega^2}{\omega_{syst}{}^2}$ (see (3.9) and (3.21)).

## 3.7 SOLUTIONS OF THE LINEARISED EQUATIONS

### THE FOURIER TRANSFORM

We are able to write (3.35) and (3.36) in a general and well-known form.

$$a_2 \ddot{y} + a_1 \dot{y} + a_0 y = b_1 \dot{x} + b_0 x \qquad (3.41)$$

To find a solution for y the Fourier transform can be used (see e.g. [8], [9] or [10]).

$$y(t) = \sum_{n=-\infty}^{n=\infty} Y_n(\omega)\cdot\exp(in\omega t)$$

$$Y_n(\omega) = \frac{1}{T}\int_0^T y(t)\cdot\exp(-in\omega t)\ dt$$

in which $Y_n(\omega)$ are complex numbers,
n are integers and
T is the time of one cycle ($\omega/2\pi$).

By definition:

$$y(t) \longrightarrow Y(\omega)$$
$$\dot{y}(t) \longrightarrow in\omega\cdot Y(\omega)$$
$$\ddot{y}(t) \longrightarrow -n^2\omega^2\cdot Y(\omega)$$

With this eq. (3.41) can be rewritten as:

$$(-n^2\omega^2 a_2+in\omega a_1+a_0)\cdot Y_n(\omega) = (in\omega b_1+b_0)\cdot X_n(\omega)$$

The transfer function $H_n(\omega)$ becomes

$$H_n(\omega) = \frac{Y_n(\omega)}{X_n(\omega)} = \frac{b_0 + in\omega b_1}{a_0-n^2\omega^2 a_2 + in\omega a_1} \tag{3.42}$$

We also can write:

$$H_n(\omega) = |H_n(\omega)|\cdot\exp(i\phi_n(\omega)) \tag{3.43}$$

in which

$$|H_n(\omega)| = \sqrt{\frac{b_0{}^2 + (n\omega b_1)^2}{(a_0-n^2\omega^2 a_2)^2 + (n\omega a_1)^2}} \tag{3.44}$$

is the amplitude of the transfer function and

$$\phi_n(\omega) = \arctan \frac{n\omega b_0}{b_1} - \arctan \frac{n\omega a_1}{a_0 - n^2\omega^2 a_2} \qquad (3.42)$$

is the phase (argument) of the transfer function.

Eqs. (3.44) and (3.45) can also be used for the dimensionless differential equations (3.38) and (3.39) if we write $A_2=\omega^2 a_2$, $A_1=\omega a_1$, $A_0=a_0$, $B_1=\omega b_1$ and $B_0=b_0$.

$$|H_n| = \sqrt{\frac{B_0^2 + (nB_1)^2}{(A_0-n^2A_2)^2 + (nA_1)^2}} \qquad (3.46)$$

$$\phi_n = \arctan \frac{nB_0}{B_1} - \arctan \frac{nA_1}{A_0-n^2A_2} \qquad (3.47)$$

Examples of the amplitude and the phase as a function of the rotational speed ratio $\omega/\omega_{syst}$, for both the flow (eq.(3.38)) and the pressure (eq.(3.39)), are shown in fig. 3.4 and 3.5. Here $\omega_{syst}$ is the natural angular velocity for the line-airchamber system at $\omega=0$, $\omega_{syst}^2 = 1/LC_{syst}$. This is done because the natural angular velocity $\omega_0$ is dependent on the rotational speed $\omega$ (see par. 3.5).
The data of the pump system are to be found in table 3.1.

Table 3.1 The data from the experiment numbers 16 to 18, see chapter 6, were used to calculate the transfer functions (fig. 3.4 and 3.5) and the output functions (fig. 3.6 and 3.7) of both the dimensionless flow and the dimensionless pressure fluctuations. No air is supplied to the airchamber.

$H_d = 10$ m
$7_{atm} = 2.30 \cdot 10^{-3}$ m$^3$
$k = 1.4$

$R_d = 4.34 \cdot 10^{10}$ kg/m$^7$
$L_d = 1.03 \cdot 10^{8}$ kg/m$^4$
$C_{syst} = 4.19 \cdot 10^{-9}$ m$^4$s$^2$/kg
$\omega_{syst} = 1.52$ rad/s

From these graphs we see that the rotational speed ratio $\omega/\omega_{syst}$ may not be chosen too small or too large. When this ratio becomes too small, resonance will appear for the first or a higher order term of the Fourier series. When the ratio becomes too large, the amplitude of the transfer functions also become large, and so do the dimensionless flow and pressure fluctuations.

Resonance in our pump system means the that water column between airchamber and outlet (for the delivery part) or inlet (for the suction part) acts like a pendulum. Dependent on the damping ratio $A_1/2\cdot\sqrt{(A_0\cdot A_2)}$ , the values of the transfer functions increase fast if $\omega$ approaches $\omega_0$.

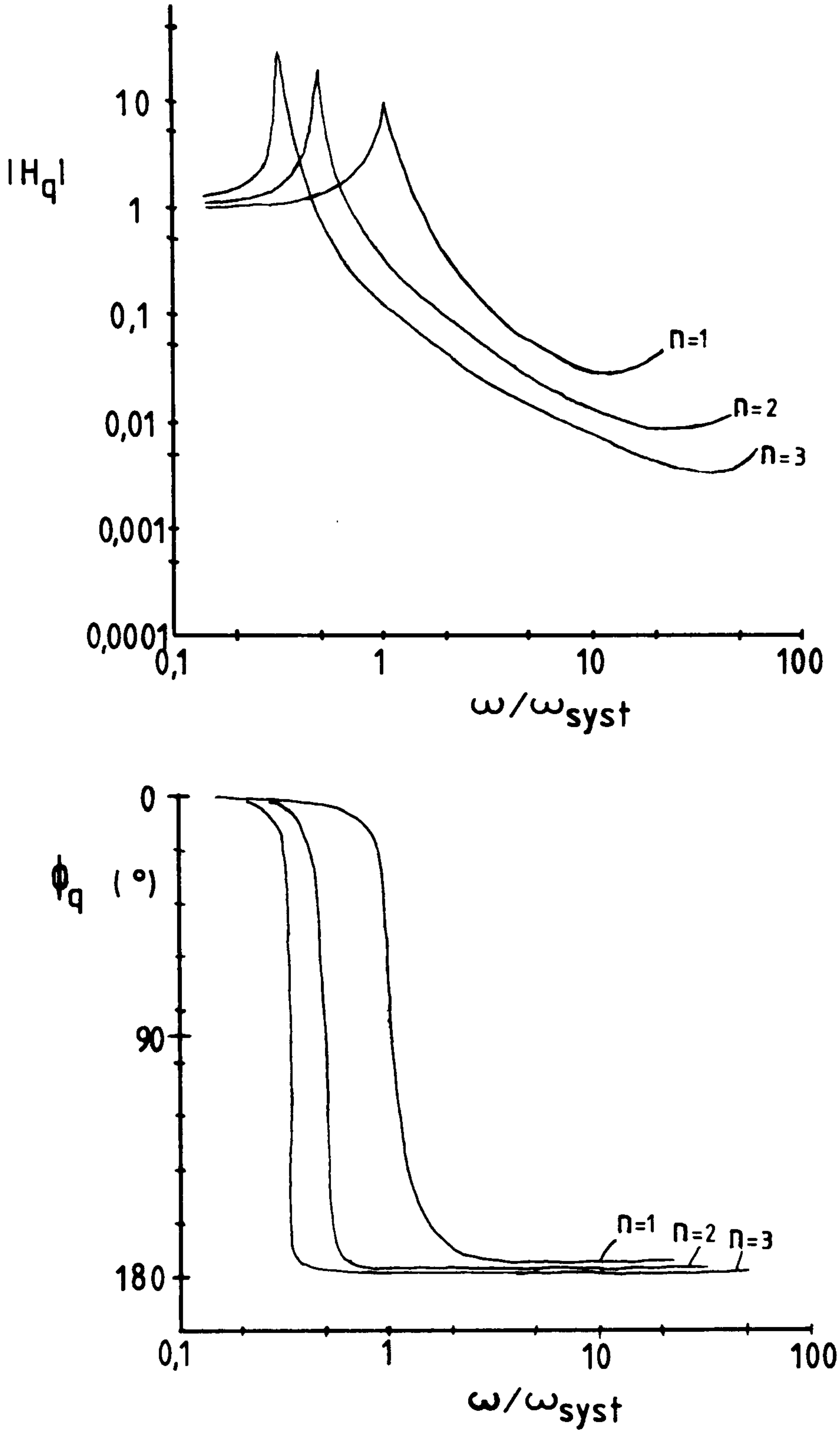


Figure 3.4 The amplitude (above) and the phase (below) of the transfer function of the flow (eq.(3.36)). Data are to be found in table 3.1 .

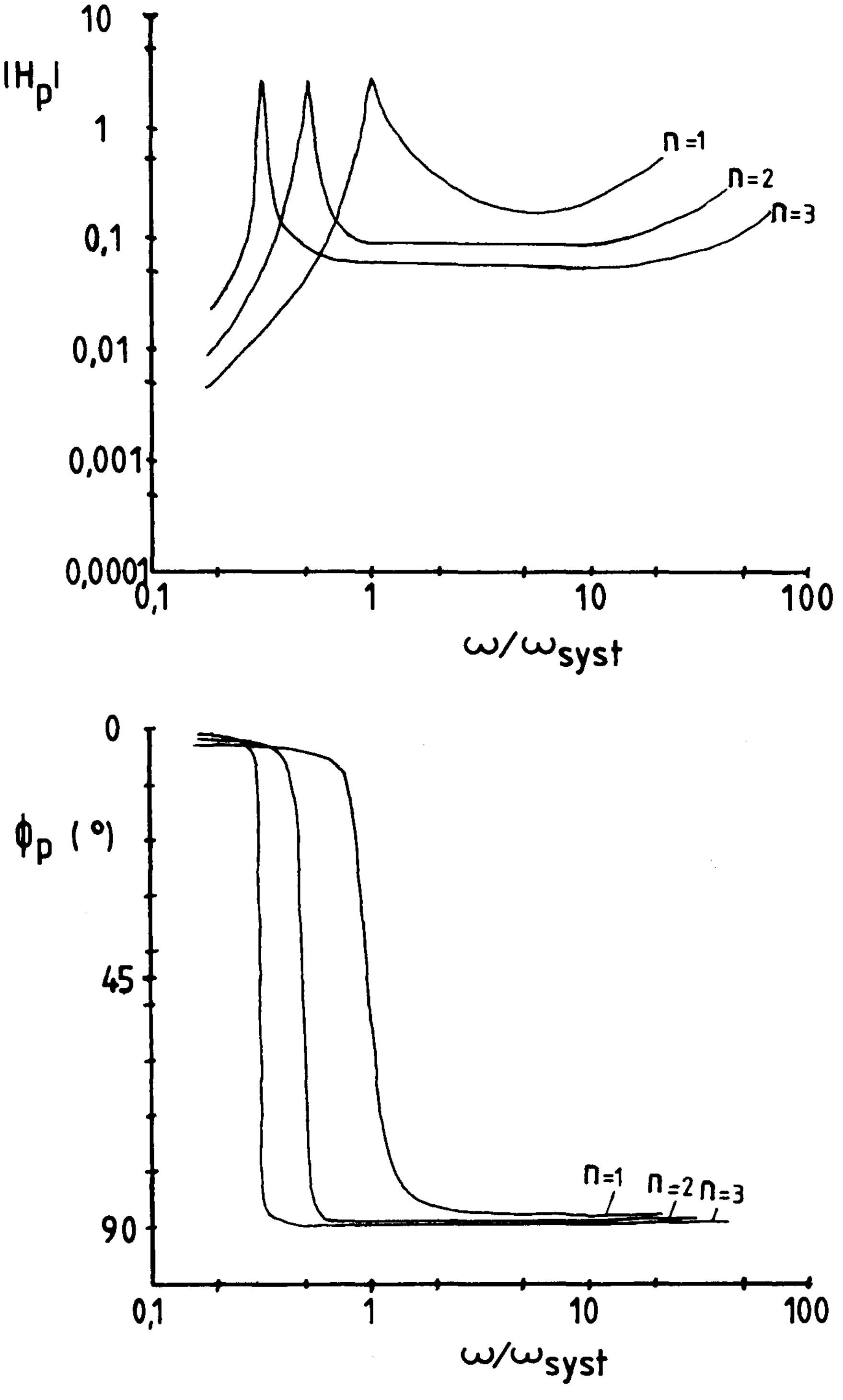


Figure 3.5 The amplitude (above) and the phase (below) of the transfer function of the pressure (eq.(3.37)). Data are to be found in table 3.1 .

## THE INPUT FUNCTION

As we have seen in paragraph 3.3 $q_c$, and so $\hat{q}_c-1$, is a periodical signal. This means $q_c$ can be written as a sum of continous sinusoidal functions with use of Fourier series ([8], p.153).

$$q_c = \bar{q}_c \left\{ 1 - \frac{i}{4}\cdot(e^{i\omega t} - e^{-i\omega t}) - \frac{1}{\pi}\cdot\left( \frac{e^{2i\omega t} + e^{-2i\omega t}}{1\cdot 3} + \right.\right.$$

$$\left.\left. + \frac{e^{4i\omega t} + e^{-4i\omega t}}{3\cdot 5} + \cdots\cdots \right)\right\}$$

$$\hat{q}_c-1 = \left\{ -\left(\frac{i\pi}{4}\right)\cdot(e^{i\hat{t}} - e^{-i\hat{t}}) - 1\cdot(\cdots)\ \cdots \right\}$$

Here $\hat{q}_c-1$ is the dimensionless input function $X_n(\omega)$ of (3.42).

## THE OUTPUT_FUNCTION OF_THE_FLOW

For n=1 the first term of the output function $\Delta\hat{q}_1$ is

$$\Delta\hat{q}_1 = \sqrt{\frac{1}{(1-A_2)^2+(2A_1)^2}}\cdot -\left(\frac{i\pi}{4}\right)\cdot\exp\left[ i\left\{ \hat{t} - \arctan\left(\frac{2A_1}{1-A_2}\right)\right\}\right]$$

If $\omega^2 >> \omega_0{}^2$ then $A_2>>1$ (far from resonance). Besides, in our case $A_1$ proved to be small compared to $A_2$, see eq. (3.40).

$$\frac{A_1}{A_2} = \frac{R\cdot\nabla_s}{2\pi\cdot L} \simeq 0.05 \text{ (see table 4.1)}$$

This means

$$\Delta\hat{q}_1 = \frac{\omega_0{}^2}{\omega^2}\cdot -\left(\frac{i\pi}{4}\right)\cdot\exp\{i(\hat{t} - \pi)\}$$

For n=2 we find

$$\Delta\hat{q}_2 = \frac{1}{4}\,\frac{\omega_0^2}{\omega^2}\cdot\frac{-1}{3}\cdot\exp\{i(2\hat{t} - \pi)\}$$

For n=-1 and n=-2 we find equal functions but of opposite sign. The third and higher terms of $\hat{q}_c-1$ are neglected because their amplitudes are very small compared to $|\Delta\hat{q}_1|$.

A good approximation of the output function of the flow thus becomes:

$$\Delta\hat{q} = \frac{\omega_0^2}{\omega^2}\cdot\left\{\frac{\pi}{2}\cdot\sin(\hat{t} - \pi) - \frac{1}{6}\cdot\cos(2\hat{t} - \pi)\right\} \qquad (3.48)$$

One can see condition 1 of p.29 is fulfilled because $\omega_0^2/\omega^2 \ll 1$ during the whole cycle.

An example of the output function is shown in fig. 3.6.

## THE OUTPUT FUNCTION OF THE PRESSURE

For n=1 the first term of the output function $\Delta\hat{p}_1$ is

$$\Delta\hat{p}_{1,1} = \sqrt{\frac{B_0^2 + B_1^2}{(1-A_2)^2 + A_1^2}}\cdot -\left(\frac{i\pi}{4}\right)\cdot\exp\left[i\left\{\hat{t} + \arctan\left(\frac{B_1}{B_0}\right) - \arctan\left(\frac{A_1}{1-A_2}\right)\right\}\right]$$

If $\omega^2 \gg \omega_0^2$ this expression can be simplified.

$$\Delta\hat{p}_{1,1} = \frac{B_1}{A_2}\cdot -\left(\frac{i\pi}{4}\right)\cdot\exp\left\{i\left(\hat{t} - \frac{\pi}{2}\right)\right\}$$

For the second term we find

$$\Delta\hat{p}_{1,2} = \frac{1}{2}\cdot\frac{B_1}{A_2}\cdot\frac{-1}{3}\cdot\exp\left\{i\left(2\hat{t} - \frac{\pi}{2}\right)\right\}$$

Here also the third and higher order terms are neglected because they are small compared to $|\Delta\hat{p}_{1,1}|$.
For n=-1 and n=-2 we find equal functions but of opposite sign.
A good approximation of the output function of the pressure thus becomes:

$$\Delta\hat{p}_1 = \frac{B_1}{A_2}\cdot\left\{\frac{\pi}{2}\cdot\sin\left(\hat{t} - \frac{\pi}{2}\right) - \frac{1}{3}\cdot\cos\left(2\hat{t} - \frac{\pi}{2}\right)\right\} \qquad (3.49)$$

From this we see that the smaller the value of $B_1/A_2$, the smaller the effect on C (eq.(3.17)) is, and more important, the smaller the pressure fluctuations acting on the pump rod are.

$B_1/A_2$ is proportional to the volume ratio $\nabla_s/\nabla_{atm}$:

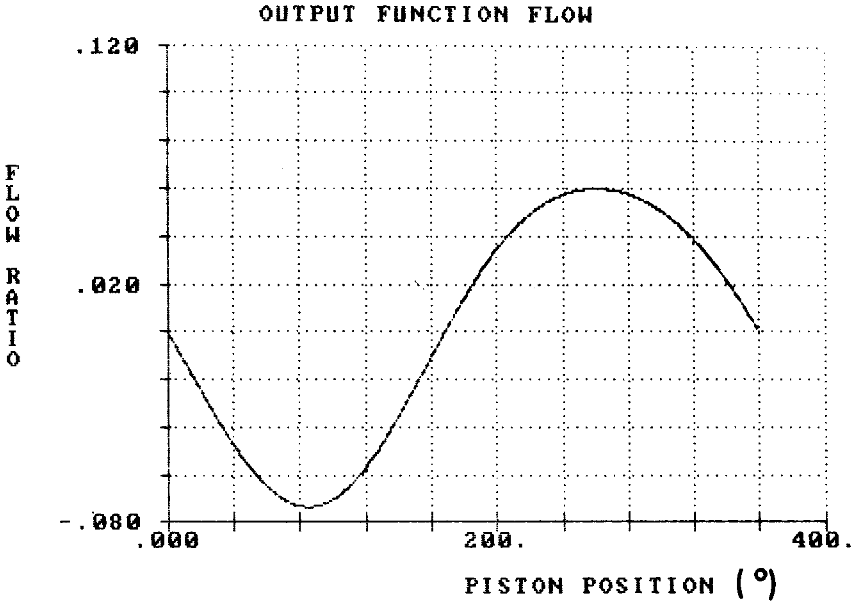
$$\frac{B_1}{A_2} = \frac{\omega L\bar{q}_c}{\bar{p}_1}\cdot\frac{\omega_0^2}{\omega^2} = \frac{\omega L\cdot\omega\nabla_s/2\pi}{\bar{p}_1}\cdot\frac{1}{\omega^2 LC_0} = \frac{k}{2\pi}\cdot\frac{\nabla_s}{\nabla_{atm}}\cdot\frac{\bar{p}_1}{p_{atm}} \qquad (3.50)$$

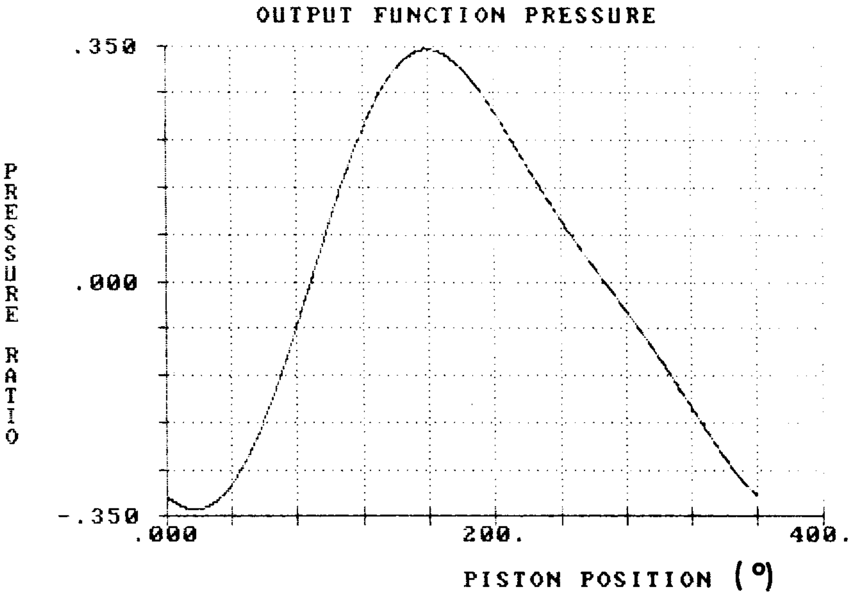
This seems to be an important rule to design piston pumps. The smaller the volume ratio, the better.

If air is supplied to the airchamber, (3.50) even become more simple. Instead of $C_0$ now $C_0'$ has to be used (see par. 3.5).

$$\frac{B_1}{A_2} = \frac{\omega L\bar{q}_c}{\bar{p}_1}\cdot\frac{\omega_0^2}{\omega^2} = \frac{\omega L\cdot\omega\nabla_s/2\pi}{\bar{p}_1}\cdot\frac{1}{\omega^2 LC_0'} = \frac{k}{2\pi}\cdot\frac{\nabla_s}{\nabla_{atm}} \qquad (3.51)$$

An example of the output function of $\Delta\hat{p}_1$ is shown in fig. 3.7.





Figures 3.6 and 3.7 Outnut functions of the dimensionless flow and pressure fluctutions, $\omega$ = 10 rad/s. Other data are to be found in table 3.1 .

# 4. DESCRIPTION OF THE PUMP TEST RIG

## 4.1 THE PUMP TEST RIG

The WEG is in the possession of a pump test rig in its laboratory for pump testing.
To check the validity of the model, described in the previous chapter, a laboratory version of the so-called Tanzania pump has been used to perform measurements. A schematic drawing of this pump and the pump test rig is shown in figure 4.1.
The data of this pump is to be found in table 4.1, p.44.

The pump test rig can be subdivided into:

- the driving unit the lines and the pressure vessel (see par. 4.2),
- the pump with airchambers (par. 4.3) and
- the transducers (par. 4.4).

The data acquisition system used for recording the measured signals is described in chapter 5.

## 4.2 THE DRIVING UNIT, THE LINES AND THE PRESSURE VESSEL

The windmill is simulated by a 380 V AC motor. One can adjust a constant rotational speed between 0 and about 15 rad/s.
The load on the motor varies very much during one cycle (see fig. 2.3). To keep a constant rotational speed, a fly-wheel is fixed to the motor shaft. A transmission, adjustable from 1:1 up to 9:1, makes it possible to keep a constant rotational speed at low speeds.

The motor shaft is coupled to the driving rod via a worm box. A rocker arm converts the movement of the driving rod into a reciprocating movement of the pump rod.

The stroke of the pump rod is adjustable from 0 up to 0.20 m.

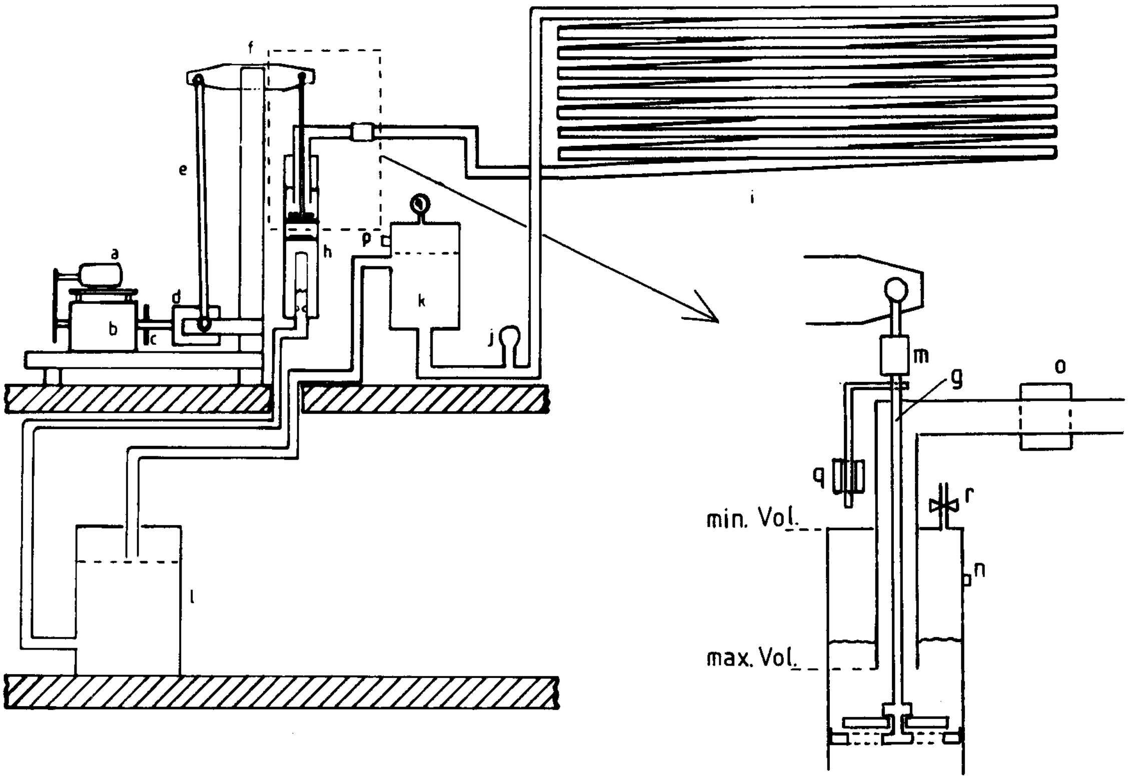


Figure 4.1 Schematic drawing of the pump test rig with the Tanzania-pump.

| | | | |
|---|---|---|---|
| a | a.c. motor | i | delivery line system |
| b | transmission | j | de-aeration pot |
| c | fly-wheel | k | pressure vessel |
| d | worm box | l | supply tank, source |
| e | driving rod | m | strain indicator |
| f | rocker arm | n,p | pressure transducers |
| g | pump rod | o | flow meter |
| h | pump with airchambers | q | speed transducer |
| | | r | air tap |

In our laboratory the pump test rig has been equipped with a delivery line system with a total length of 104 m. Together with a pressure vessel we are able to simulate a delivery head of about 100 m.

## 4.3 THE PUMP

The pump rod and the perspex pump cylinder both limit the delivery head. The pump rod may not be loaded over 8 kN and the perspex cylinder cannot stand an excess pressure of more than 2.5 bar.
In our case the perspex cylinder limits the delivery head to about 20 m. (The pressure difference due to the flow resistance and acceleration of the water mass has to be taken into account too.)

The air volume of an airchamber turned out to be an important parameter in the model of chapter 3. For this reason, an air tap is mounted to the delivery airchamber with which it is possible to adjust a delivery airchamber volume from 0 up to $4.7 \cdot 10^{-3}$ $m^3$.

The configuration of fig. 4.1 offers the following possibilities:

- variable rotational speed (0-15 rad/s),
- variable stroke (0-0.20 m),
- variable delivery head (0-20 m) and
- variable airchamber volume ($0\text{-}4.7 \cdot 10^{-3}$ $m^3$).

Table 4.1 The data of the pump of fig. 4.1. The data is subdivided into three parts, the suction part, the delivery part and the pump cylinder part (see par. 3.2, p.18). $C_{syst}$ and $\omega_{syst}$ of the delivery part aren't given, because they are dependent on the delivery head and the air volume of the delivery airchamber (see par. 3.5).
Data was obtained from Hilbers [11].

| | SUCTION PART | DELIVERY PART | PUMPCYLINDER PART |
|---|---|---|---|
| stroke (m) | - | - | 0.05 - 0.20 |
| volume airch/str ($m^3$) | $3.40 \cdot 10^{-3}$ | 0 - $4.70 \cdot 10^{-3}$ | $7.60 \cdot 10^{-4}$ |
| length (m) | $7.50 \cdot 10^{0}$ | $1.04 \cdot 10^{2}$ | $9.00 \cdot 10^{-1}$ |
| diameter (m) | $5.30 \cdot 10^{-2}$ | $3.59 \cdot 10^{-2}$ | $1.40 \cdot 10^{-1}$ |
| cr-sect area ($m^2$) | $2.21 \cdot 10^{-3}$ | $1.01 \cdot 10^{-3}$ | $1.54 \cdot 10^{-2}$ |
| height (m) | $1.85 \cdot 10^{0}$ | 0 - $2.00 \cdot 10^{1}$ | $9.00 \cdot 10^{-1}$ |
| R ($kg/m^7$) | $5.24 \cdot 10^{8}$ | $4.34 \cdot 10^{10}$ | $8.31 \cdot 10^{7}$ |
| L ($kg/m^4$) | $3.40 \cdot 10^{6}$ | $1.03 \cdot 10^{8}$ | $9.24 \cdot 10^{4}$ |
| $C_{syst}$ ($m^4 s^2/kg$) | $1.73 \cdot 10^{-8}$ | - | - |
| $\omega_{syst}$ (rad/s) | $4.13 \cdot 10^{0}$ | - | - |

## 4.4 THE TRANSDUCERS AND CALIBRATION MEASUREMENTS

The pump test rig has been equipped with:

- a strain indicator to measure the pump rod force,
- a velocity transducer, which measures the velocity of the pump rod (With this the rotational speed can be calculated.),
- a flow meter, to measure the flow in the delivery line, and
- two pressure transducers, to measure the pressure in the delivery airchamber and the pressure in the pressure vessel (delivery head!).

## THE PUMP_ROD_FORCE

The pump rod force is measured with an EBM (E. Brosa Messgeräte) strain indicator (max. range 10 kN). The signal is amplified and transposed with a Peekel transducer/strainindicator CA 300.
The maximum output voltage is 1.0 V. To obtain satisfactory accuracy at low loads, five different amplification ranges can be selected. The zero offset is also adjustable.

The strain indicator, coupled to the transducer, has been calibrated in a calibration rig at the Department of Mechanical Engineering*.
The inaccuracy of the calibration rig is 0.5 % full scale. Together with an inaccuracy of the offset of the x,t-recorder (0.25 % f.s.) and of the read value (0.25 % f.s.), the inaccuracy becomes 1.0 % full scale.
The final results, in numerical form, are shown in table 4.2.

Table 4.2 The calibration of the strain indicator coupled to the Peekel transducer/strainindicator. Both the ranges of the amplifier and the calibration rig are given. The calibration coefficient (in N/V) is the ratio between the force on the strain indicator (F) divided by the output voltage of the amplifier (U).

| | | | | |
|---|---|---|---|---|
| range amplifier (-) | 300 | 1000 | 3000 | 10000 |
| range calibr. rig (kN) | 2.00 (±.01) | 2.00 (±.01) | 5.00 (±.025) | 10.0 (±.05) |
| cal. coeff. (N/V)$*10^3$ | .789 (±1.%) | 2.61 (±1.%) | 7.77 (±1.%) | 25.9 (±1.%) |

---

* The testing has been performed in cooperation with C.Meesters of the Group of Material Engineering of the Department of Mechanical Engineering.

With these results we can write

$$F = 2.60\ (\pm\ 0.026) * U \qquad (4.1)$$

in which F is the force on the strain indicator (in N),
U is the output voltage of the amplifier (in V) and the value 2.60 is the calibration coefficient divided by the range of the amplifier.

The calibration curves are to be found in Appendix 4A.

## THE VELOCITY_OF THE PUMP_ROD

The velocity of the pump rod is measured with a Schaevitz 7L10VT-Z linear velocity transducer (moving magnet pickup). The great advantage of a moving magnet pickup is that it has no zero offset.

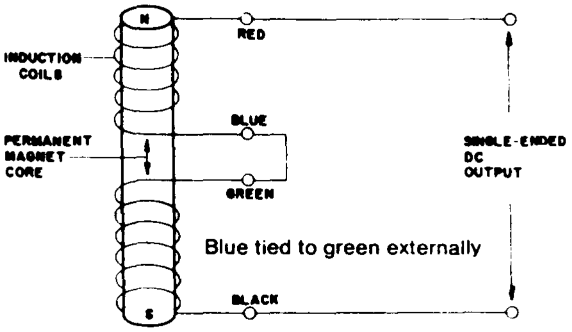
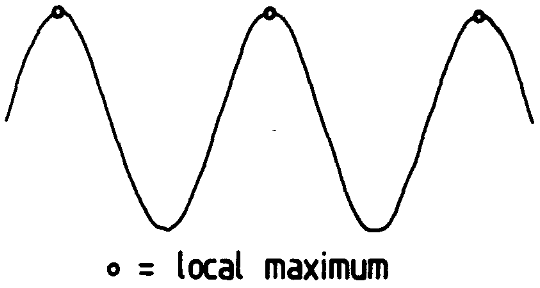


Figure 4.3 Sketch of a moving magnet pickup.

The transducer has been calibrated with use of the IBM personal computer and a stopwatch at 10 different rotational speeds. The number of revolutions was counted during a certainamount of time (at least least 30 s). The inaccuracy is estimated to be less than 1% .

From the output voltage of the transducer, five local maxima are calculated by the computer. The inaccuracy is 0.1 % * 10 V = 0.01 V.



The following relation was found:

$$v = 0.125\ (\pm\ 0.0013) * U \pm 0.0013 \qquad (4.2)$$

in which v is the velocity of the pump rod (in m/s) and
U is the output voltage of the velocity transducer.

## THE FLOW_METER

The flow in the delivery line is measured with an Endres & Hauser Speedmag measuring unit. This unit consists of a flow meter with a gain amplifier (DI 651) and a programmable micro processor (ZL 6520). For detailed information, see [12].

The Speedmag is a magnetic inductive flow meter which can measure the flow up to 250 times per second. With this meter it is possible to obtain the course of the flow during one cycle.

The measurement principle is based on the induction law of Faraday (see also fig. 4.4). If a conductor (conductive fluid) with length l (diameter of the flow meter) moves with a transverse velocity v (velocity of the fluid) across a magnetic field of intensity B, there will be forces acting on the charged particles of the conductor. The possitive charges will move toward one end of the conductor and the negative charges to the other end. Thus a potential gradient is set up along the conductor, and there is a voltage difference e between its two ends.

The quantative relation among the variables is given by the well-known equation

$$e = B \times l \times v \qquad (4.3)$$

in which e is the voltage difference between the two ends of the conductor,

B is the field flux density (in $Wb/m^2 = V{\cdot}s/m^2$),

l is the conductor length and

v is the conductor velocity.

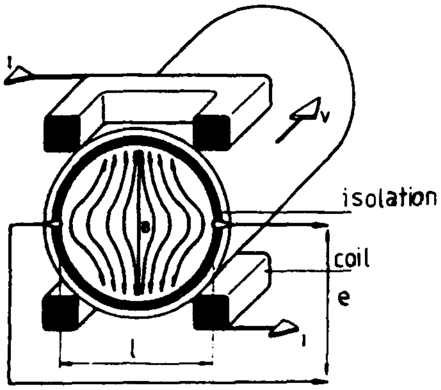


Figure 4.4 The principle of the flow meter.

The induced voltage in the fluid is measured with two isolated electrodes. The lenght l is constant. The induced voltage e is proportional to the magnetic induction B and the velocity of the fluid v. The magnetic induction is known, so with the voltage, the mean velocity can be calculated and with this the flow.

Several functions can be programmed with the micro processor, e.g.

- the measuring range,
- a noise reduction rate,
- a time constant,
- the direction of the flow (the Speedmag operates in two directions),
- etc.

However, up to now a good manual does not exist. Not all of the functions are therefore well understood. Probably this problem will be solved in the near future.

The Speedmag caused a much bigger problem. It appears that the Speedmag displays a flow of sometimes ± 0.1 $dm^3/s$ (at a measuring range of 1.00 $dm^3/s$) at the moment the flow is zero (when the motor is off). This makes the results of the flow measurements very unreliable.

## THE PRESSURE_TRANSDUCERS

The pressure in the delivery line and the pressure in the pressure vessel are measured with Kulite IPT 750-100-SG differential pressure transducers. Their range is 100 psi ($\simeq$ 7 bar). The transducers are coupled to an amplifier made by a staff member of the Laboratory of Fluid Dynamics And Heat Transfer. Three pressure transducers can be coupled to this amplifier.

The transducers coupled to the amplifier have been calibrated in a pressure calibration rig. Another pressure transducer, a Kulite IPT 750-50-A absolute pressure transducer, with a range of 50 psi ($\simeq$ 3.5 bar) has also been calibrated.

The linearity of the amplifier has been adjusted in a way that

1.00 bar corresponds with 1.00 V output. The zero offset is rather sensitive to temperature fluctuations. Therefore it must be readjusted at least twice a day when measuring.

The inaccuracy of the calibration rig is about 1%. An inaccuracy of ± 0.005 V (≡ 0.005 bar) for the zero offset is reasonable. So

$$p = 1.00\ (\pm\ 0.01) * U\ \pm\ 0.005 \qquad (4.4)$$

in which p is the pressure on the pressure transducer and
U is the output voltage of the amplifier.

The calibration curves are to be found in Appendix 4B.

# 5. DATA ACQUISITION AND ELABORATION

In this chapter the system for data acquisition and elaboration is described. In the first paragraph the data acquisition equipment is discussed. A computer program, MEASURE.DMO, has been written to collect and process data on pumps in the pump test rig. In the second and third paragraph the set up and a brief description of this program are given.

## 5.1 DATA ACQUISITION

About a year ago it was decided to replace the outdated measuring system of the pump test rig with more modern and practical equipment.

Several measuring systems were tested (see [4] and [5]). The decision was made to buy an IBM XT Personal Computer equipped with a MetraByte Dash-16 data acquisition board, an Intel 8087 Math Co-Processor and a Hercules Graphics Card. An Epson FX-105 printer is connected to the computer to print text and graphics. Further an extensive scientific software package, called ASYST, was bought to collect and process data.
With this system up to 16 signals can be measured (by sampling) and elaborated.

The MetraByte board can be used with different options (see Appendix 5A). In the present situation the following options are used:

- 4 channels, single ended
- +/- 10 V bipolar input range
- conversion time controlled by software

The +/- 10 V input range has a 12 bit resolution, which equals 4096 numbers. The A/D converter has been calibrated with a Datel Voltage Calibrator (DVC 8500) with an accuracy of ± 0.5 mV. Using linear regression the following relation between digital value (Dig) and the input voltage (U (in V)) was obtained :

$$\text{Dig} = 2045.78 + 204.75 * U \qquad (5.1)$$

Using software to control data acquisition the sampling frequency is limited to 400 Hz.

One of the main reasons ASYST has been bought, is the possibility of this package to calculate and operate with arrays in an easy and fast way.
An other advantage is the great number of built-in procedures which makes programming easier.

## 5.2 THE SET UP OF THE COMPUTER PROGRAM, MEASURE.DMO

The data to be collected concern the pump rod force, the velocity of the pump rod, the flow through the pump system and the pressure at two places in the system (see chapter 4.).

We are interested in the course of the signals during one cycle as a function of several parameters.

The developed computer program has to fulfil the following tasks:

1 - 4 signals must be measured simultaneously,
2 - sample frequency >> rotational frequency to get enough information from the signals,

3 - enough samples to obtain at least one cycle,
4 - the possibility to store and restore data of measurements and data of the pump,
5 - the data must be presented in a proper way and
6 - anyone without having prior knowledge of ASYST must be able to use the program.

Ad 1. This means the MetraByte must be "told" that it has to measure four signals. The data has to be arranged in a way that it is easy to isolate one signal.
Ad 2. One must have the possibility to choose a sample frequency.
Ad 3. Idem for the number of samples.
Ad 4. Idem for the pump data. Besides the data must be written into a file which is stored on disk.
Ad 5. When presented in a graphic the correct scaled axes have to correspond to the correct signal. When presented numerically, the right information has to be given together with the data. At the moment the graphs can only be put on paper with a printer, which alas, is not very neat.
Ad 6. The program has to direct what steps can be taken. For this reason the program is menu driven.

The program is subdivided into two blocks. In the first block one can measure the signals, write data to files and read data from files. In the second block one can obtain data on screen and/or on printer both numerically and graphically.
An overall view of the program is given as a flow diagram in fig. 5.1.

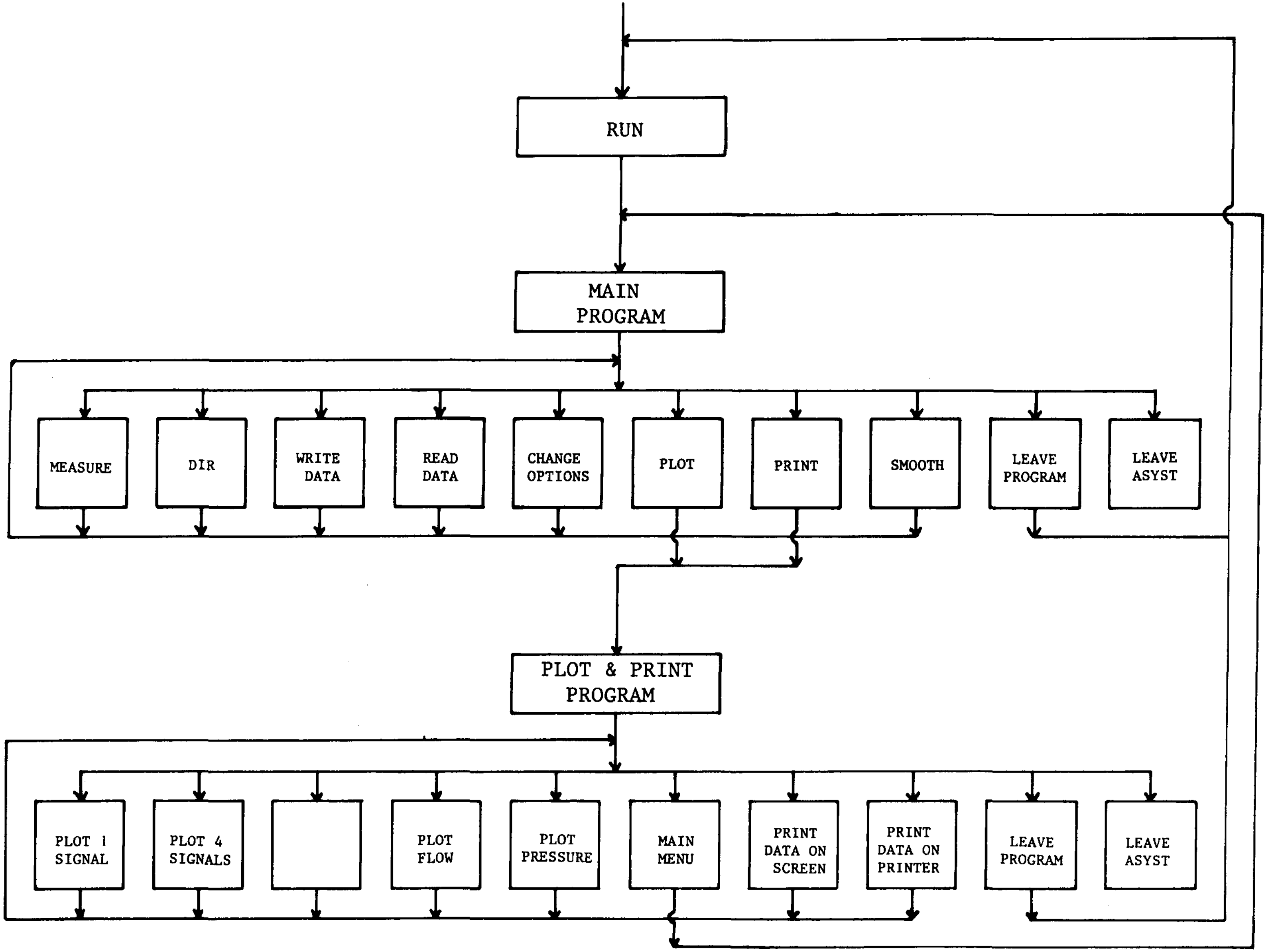


Figure 5.1 Block diagram of the computer program.

## 5.3 A BRIEF DESCRIPTION OF THE COMPUTER PROGRAM

In this paragraph the words in each block of fig. 5.1 are explained briefly.

| | |
|---|---|
| RUN | Type this word in to start the program. The main menu is displayed on the screen telling you which function corresponds with which function key. |
| MAIN PROGRAM | The functions MEASURE, DIR, etc. are installed in the function keys F1, F2, etc. |
| PLOT&PRINT PROGRAM | The functions PLOT 1 SIGNAL etc. are installed in the function keys F1, F2, etc. |

### The function_keys

| | |
|---|---|
| MEASURE | Measures the four signals connected to the first four channels on the MetraByte board. This is done with the chosen sample time and the number of given samples. |
| DIR | Displays the files saved on the floppy disk in drive B on the screen. |
| WRITE DATA | Writes the measured data and all important information of the pump together with the experiment number into a file and stores this file on the disk in drive B. |
| READ DATA | Reads a file from the disk in drive B so that one can plot or print the previously measured and stored data. The data will remain in this file which on its turn remains on the disk. |

| | |
|---|---|
| CHANGE OPTIONS | If one wants to change:<br>- the sample time,<br>- the number of samples,<br>- the range of the Transducer/Strain-indicator,<br>- the measuring range of the flow meter,<br>- the delivery head or<br>- the indication of the volume of air in the airchamber. |
| PLOT | Takes one to the PLOT&PRINT PROGRAM. |
| PRINT | See PLOT. |
| SMOOTH | Smooths the data to reduce noise signals. |
| LEAVE PROGRAM | Leaves the program so one still is able to work with ASYST. |
| LEAVE ASYST | Leaves ASYST if one wants to work with DOS or another software package. |

| | |
|---|---|
| PLOT 1 SIGNAL | Plots one signal, out of four measured, on the screen. |
| PLOT 4 SIGNALS | Plots all four signals on the screen in small vuports. |
| PLOT FLOW | Calculates the theoretical output function of the flow in the delivery line, using the last measured or last restored measured data as input data. Before one is able to use this function, the program COMPARE.DAT first must be loaded. (See also Appendix 5B and 5C.) |
| PLOT PRESSURE | Idem for the output function of the pressure in the delivery airchamber. |
| MAIN MENU | Takes one back to the MAIN PROGRAM. |
| PRINT DATA ON SCREEN | Lists the important information of the pump and after that the measured data on the screen. |
| PRINT DATA ON PRINTER | Prints the pump data on the printer. |

The entire program together with some explanatory text is to be found in Appendix 5B.

The program is written and saved in the file MEASURE.DMO and stored on the disk WORKDISK2. A back-up of this file is on the same disk with the name MEASURE.BAK. A copy of the file is saved on the disk WORKDISK3.
A compiled version of the program is saved on the disk MEASURE.

A User's Guide is to be found in Appendix 5C.

# 6. THE EXPERIMENTS

## 6.1 SET UP AND PERFORMANCE

The model of chapter 3. has lead to short expressions for both the dimensionless flow fluctuations in the lines and the dimensionless pressure fluctuations at the cross-sections $d_0$ and $s_0$ (see fig. 3.1).

$$\hat{\Delta q} = \frac{\Delta q}{\bar{q}_c} \sim \frac{\omega_0^{\,2}}{\omega^2} \qquad (3.48)$$

$$\hat{\Delta p}_1 = \frac{\Delta p_1}{\bar{p}_1} \sim \frac{\nabla_s}{\nabla_{atm}} \cdot \frac{\bar{p}_1}{p_{atm}} \qquad \text{(without air supply)} \qquad (3.50)$$

$$\hat{\Delta p}_1 = \frac{\Delta p_1}{\bar{p}_1} \sim \frac{\nabla_s}{\nabla_{atm}} \qquad \text{(with air supply)} \qquad (3.51)$$

With use of measurements made by Hilbers [11], the following values of the flow resistance and line inertias have been calculated for the Tanzania-pump (see also table 4.1):

$R_c$ = 8.22E+06 $kg/m^7$ , $L_c$ = 4.22E+04 $kg/m^4$
$R_s$ = 8.22E+08 " , $L_s$ = 4.33E+06 "
$R_d$ = 4.34E+10 " , $L_d$ = 1.03E+08 "

Looking at the pressure fluctuations, the greatest support to the hydrodynamic force of eq. (3.1) is to be expected from the delivery part.
Therefore the measurements have been executed on the delivery part of the pump, see also chapter 4.

From (3.50) and (3.51) it must be interesting to look at:

1 - the influence of $\nabla_s/\nabla_{atm}$,
2 - the influence of $\overline{p}_1$ ($H_d$, $\omega$), see (3.9)
3 - the influence of resonance and
4 - the influence of a constant $\overline{\nabla}$ (air supply), i.e. independent of $\omega$.

For points 1 and 2 it has been decided to obtain measurements for three different $\nabla_{atm}$'s, i.e. 4.61, 2.30 and 1.15 $dm^3$. For each of these volumes three different delivery heads were adjusted, i.e. 1.0, 5.0 and 10.0 m, at three different speeds for each of these heads. The numerical results are to be found in table 6B.1, experiments 1 to 27 of Appendix 6B.

For point 3, an airchamber volume of 1.15 $dm^3$ and a delivery head of 10.0 m were adjusted. This means $\omega_{syst}$=2.15 rad/s. At low rotational speeds, $\omega_0$ will not be much greater than $\omega_{syst}$ (see fig. 3.3). Three measurements has been obtained with rotational speeds close to 2 rad/s, see table 6B.1, experiments 28,29 and 30.

To obtain useful information on the influence of the way air is supplied to an airchamber (point 4), two measuring series have been performed (31 up to 35). These measurements can be compared with both the theory and the experiments 13 up to 18, see table 6B.1 of Appendix 6B.

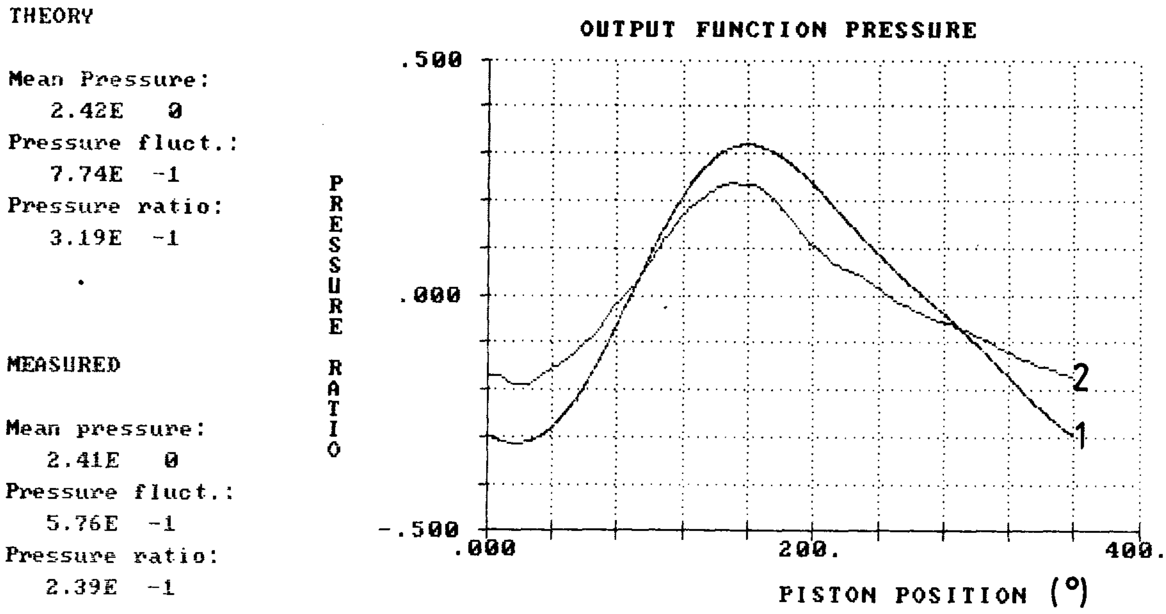
The files in which the data of all these measurements is saved, are stored on the disks DATA.2 and DATA.6 .

Another question concerned the gas constant k. Is the air in the airchamber compressed and expanded isothermally or adiabatically? From measurements, table 6A.1 in Appendix 6A, it looks as if the compression and expansion takes place adiabatically, so $k=\gamma=1.4$ (for air).

## 6.3 THE RESULTS OF THE PRESSURE MEASUREMENTS

We assumed the pressure in the delivery airchamber to be equal to the pressure in the delivery line ($p_a$ = $p_{d1}$, par. 3.5). The easiest way to measure the pressure was to mount a pressure transducer in the wall of the airchamber.

Although a lot of experiments have been performed, only one measurement has been analysed in more detail, i.e. experiment 18 (see tables 6B.1 and 6B.2 ). This was due to a lack of time. A few other measurements are presented as graphs in Appendix 6C. From experiment 18 one cycle was extracted to compare this measurement with the theoretical values of the model. The course of both the measured and the calculated pressure fluctuation during one cycle is shown in fig. 6.1 .



THEORY

Mean Pressure:
2.42E 0
Pressure fluct.:
7.74E -1
Pressure ratio:
3.19E -1

MEASURED

Mean pressure:
2.41E 0
Pressure fluct.:
5.76E -1
Pressure ratio:
2.39E -1

Figures 6.1 The course of the output functions of the pressure both of the model and of the measurement result of experiment 18. Data are to be found in table 6.1 .
1: theory , 2: measurement

Table 6.1 The data of the pump system during experiment 18.

|  | SUCTION | DELIVERY | PUMP |  | GENERAL |
|---|---|---|---|---|---|
| STROKE | 0.00E -1 | 2.50E -1 | 5.00E -2 | RO WATER | 1.00E 3 |
| AIRCH/STR VOL | 3.40E -3 | 2.30E -3 | 7.70E -4 | ATM PRESSURE | 1.01E 5 |
| LENGTH | 7.50E 0 | 1.04E 2 | 9.00E -1 | GAS CONSTANT | 1.40E 0 |
| DIAMETER | 5.30E -2 | 3.59E -2 | 1.40E -1 | RANGE FORCE Tr/S | 3.00E 3 |
| CROSS-SECTION | 2.21E -3 | 1.01E -3 | 1.54E -2 | RANGE FLOW Trans | 2.00E 0 |
| HEAD | 1.85E 0 | 1.00E 1 | 1.17E 0 | TOTAL HEAD | 1.30E 1 |
| LAMBDA | 2.90E -2 | 2.90E -2 | 3.00E -2 | STATIC FORCE | 1.97E 3 |
| CHI | 1.00E 0 | 5.00E 0 | 3.94E 1 | ONE SAMPLE (ms.) | 4.00E 0 |
| R | 5.24E 8 | 4.34E 10 | 8.31E 7 | NUMBER SAMPLES | 1.93E 2 |
| L | 3.40E 6 | 1.03E 8 | 9.42E 4 |  | 0.00E -1 |
| Csystem | 1.73E -8 | 4.19E -9 | 0.00E -1 | AIR SUPPLY | 0.00E -1 |
| wsystem | 4.13E 0 | 1.52E 0 | 0.00E -1 | ROTATIONAL SPEED | 1.00E 1 |

| MEAN FLOW | FLOW FLUC | MEAN PRES | PRES FLUC |
|---|---|---|---|
| 8.08E -1 | 2.86E -1 | 2.41E 0 | 5.76E -1 |

The similarity between the theoretical and the measured pressure fluctuation is striking. The maxima are both found at $\omega t \simeq 2.8$ rad (160°), the minima at $\omega t \simeq 0.35$ rad (20°). There is only a slight difference between the maximum values of the fluctuations.

From the other experiments only the maxima of the dimensionless pressure fluctuations are compared with the calculated values of the model. The results are presented in figure 6.2 and in the columns 8 to 10 of table 6B.2. The theoretical values are only valid for $\omega^2 >> \omega_0^2$.

In fig 6.2 the maximum of the dimensionless pressure fluctuation has been presented as a function of $\bar{p}/p_{atm}$ for different values of the volume ratio $\nabla_s/\nabla_{atm}$.

In table 6B.2 also the ratio between the measured and theoretical values of the maxima of the dimensionless pressure fluctuations is given. This ratio is $\simeq$ 0.80, which is about equal to the value of the volumetric efficiency (see table 6B.2).

The dotted lines of fig. 6.2 correspond with the theoretical values multiplied by this constant 0.80 .

In fig. 6.3 also a new comparison is made using the constant 0.80 .

The inaccuracy of the calculated theoretical values is 10% and for the measured values about 3% (the calculations are to be found in Appendix 6B).

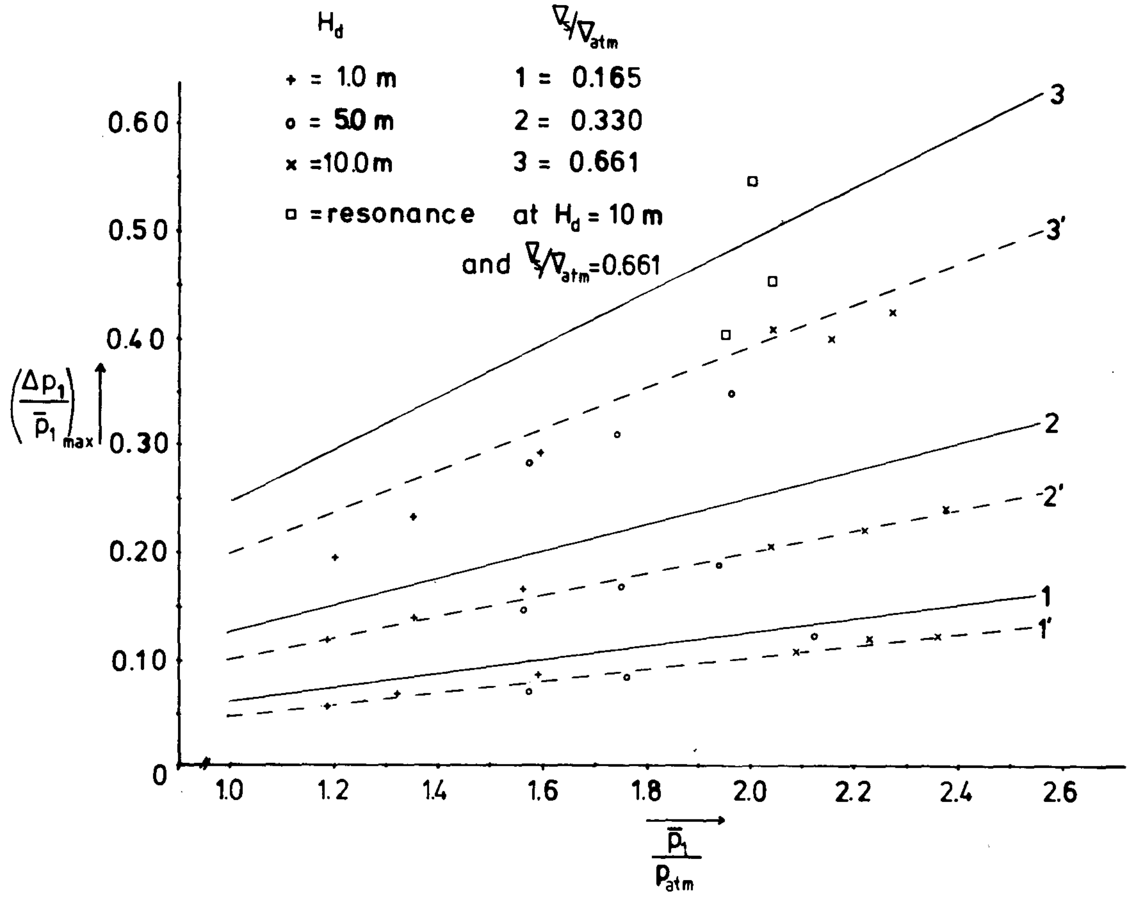


Figure 6.2 The maximum of the dimensionless pressure fluctuation in the delivery airchamber as a function of $\bar{p}_1/p_{atm}$ at different volume ratios $\nabla_s/\nabla_{atm}$. The dotted lines correspond with the theoretical values multiplied by 0.80 (volumetric efficiency).

```
THEORY

Mean Pressure:
   2.42E   0
Pressure fluct.:
   7.74E  -1
Pressure ratio:
   3.19E  -1


MEASURED

Mean pressure:
   2.41E   0
Pressure fluct.:
   5.76E  -1
Pressure ratio:
   2.39E  -1
```

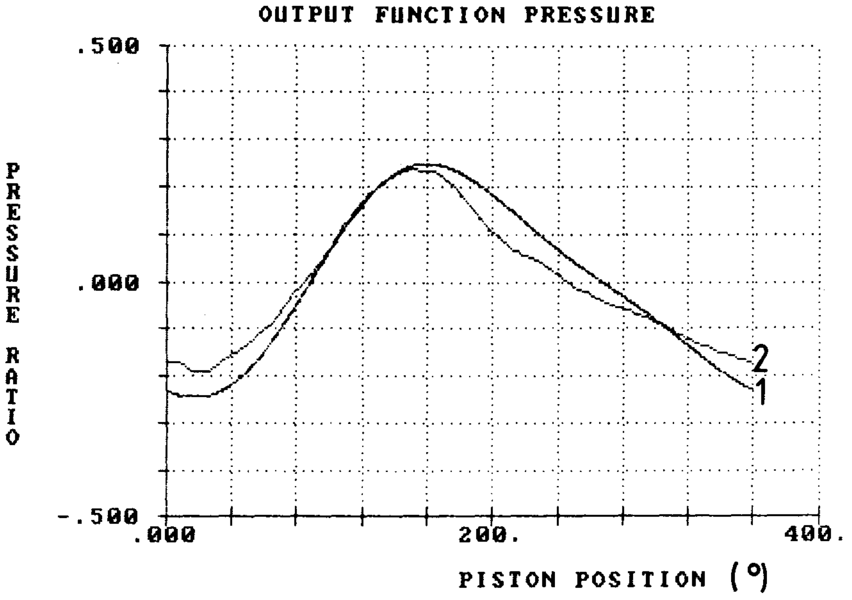
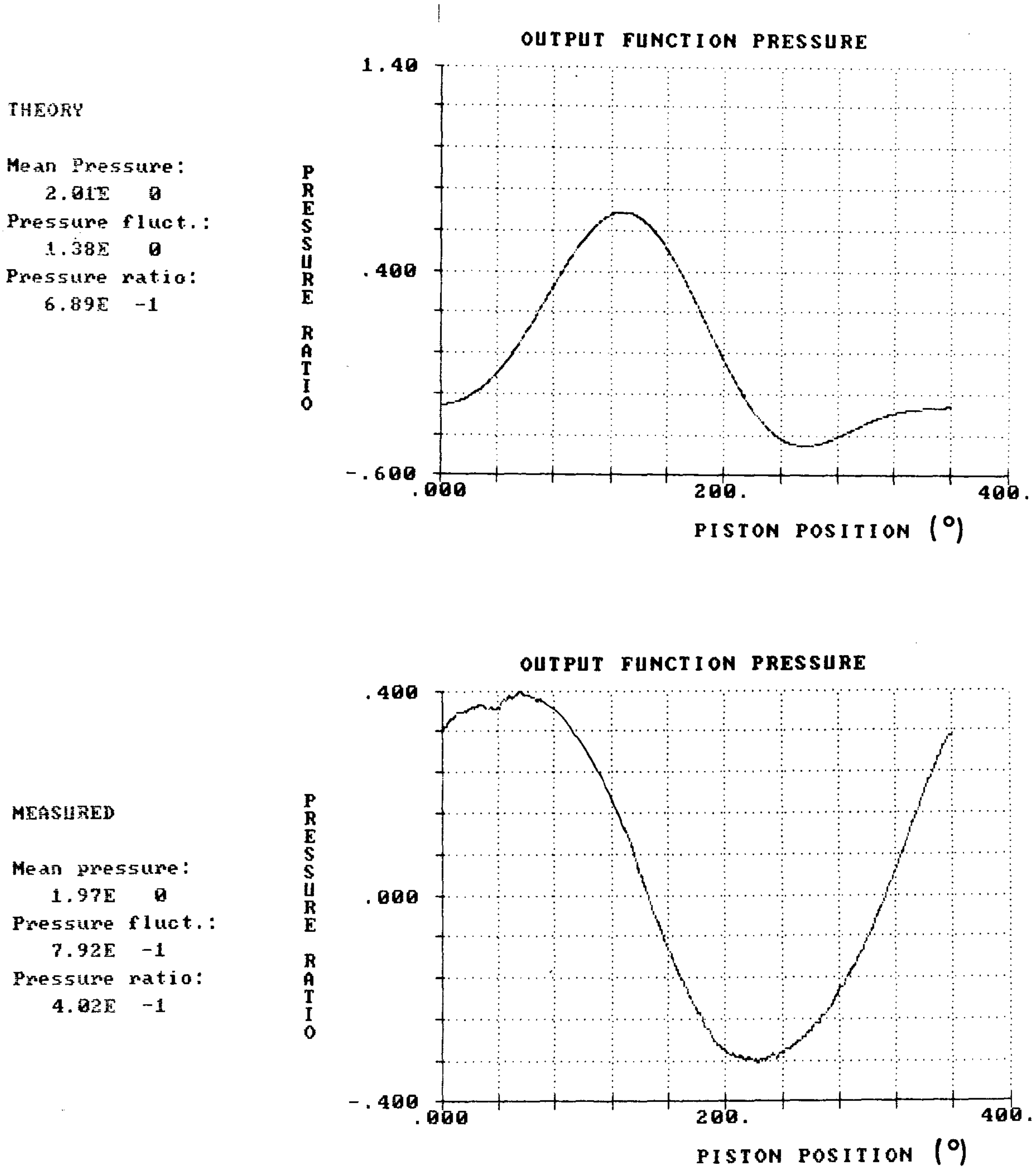


Figure 6.3 Comparison of the corrected theoretical values with the measured values of experiment 18.
1: theory , 2: measurement

RESONANCE

The results of experiments 28 to 30 shows that with rotational speeds near the rotatinal resonance speed, the dimensionless pressure fluctuations increases (see fig. 6.2). But both the phase angle and the amplitude are not right predicted with the model as can be seen from fig. 6.4 . Nonlinear terms no longer can be neglected if $\omega \simeq \omega_0$.



THEORY

Mean Pressure:
2.01E 0
Pressure fluct.:
1.38E 0
Pressure ratio:
6.89E -1

MEASURED

Mean pressure:
1.97E 0
Pressure fluct.:
7.92E -1
Pressure ratio:
4.02E -1

Figure 6.4 The course of the dimensionless pressure fluctuation during one cycle at $\omega$=1.57 rad/s, $\omega_0$=2.17 rad/s, $H_d$=10 m and $\nabla_s/\nabla_{atm}$=0.661 . Theory (above) and measurement (below).

## AIR SUPPLY

Two measuring series, experiments 31 up to and including 35, were performed in which the air volume in the delivery airchamber was kept constant, i.e. independent of the rotational speed. For experiments 31 to 33, a delivery head of 5.0 m and a volume ratio $\nabla_s/\nabla_{atm}$ of 0.49 was adjusted. For the last two experiments a delivery head of 10.0 m and a volume ratio of 0.65 was adjusted. The results of these experiments together with the results of experiments 13 to 18 are shown in fig. 6.5 .
Here too the ratio between measured and theoretical calculated values of the maximum pressure fluctuations is about equal to the value of the volumetric efficiency, $\eta \simeq 0.80$ . The dotted lines in fig. 6.5 correspond with the corrected theoretical values.
With these corrections the similarity between model and experimental results is found again.

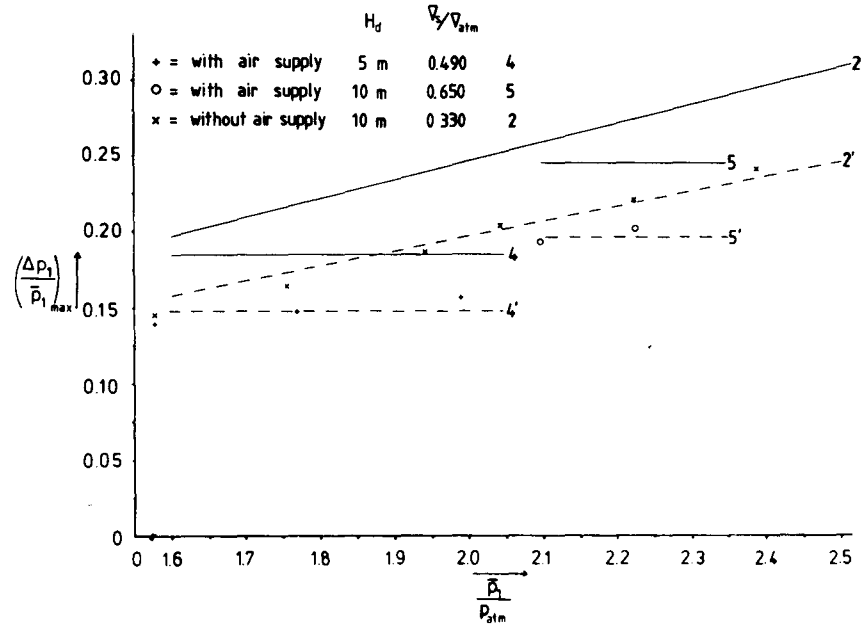


Figure 6.5 The maximum of the dimensionless pressure fluctuation in the delivery airchamber as a function of $\bar{p}_1/p_{atm}$. The dotted lines correspond with the corrected theoretical values, i.e. multiplication by the constant 0.80 .

So, if air is supplied to the (delivery) airchamber in such a way that the air volume is kept constant independent of the mean pressure, i.e. independent of delivery head and of the rotational speed, the dimensionless pressure fluctuation is only dependent on the volume ratio $\nabla_s/\nabla_{atm}$ !

## 6.2 THE RESULTS OF THE FLOW MEASUREMENTS

As said in par. 4.4, the results of the flow measurements are not very reliable. The flow meter shows an inaccuracy of ±0.1 $dm^3/s$, which is in the same order of the flow fluctuations we expect from the model.
It is therefore difficult to make a conclusion about the model with regards to the flow. In spite of this it is suspected that the model isn't set up right (see values of the columns 8 to 10 in table 6B.3). Especially the description of the flow in and out of an airchamber is far more complex as is predicted with the model. This point need further investigation.

Moreover the maximum of the dimensionless pressure fluctuation most of the times becomes more than 10% . A linear approach of the differential equations thus becomes less justified.

The course of the flow in the delivery line during one cycle is shown in fig. 6.6 for both the theoretical and the measured values. The relative high frequency signal in the measured flow fluctuation is probably due to an inproper functioning of the flow meter.

The ratio between the measured and the theoretical value of the mean flow is called the volumetric efficiency $\eta_{vol}$. The volumetric efficiency as a function of the rotational speed is shown in fig. 6.7 .

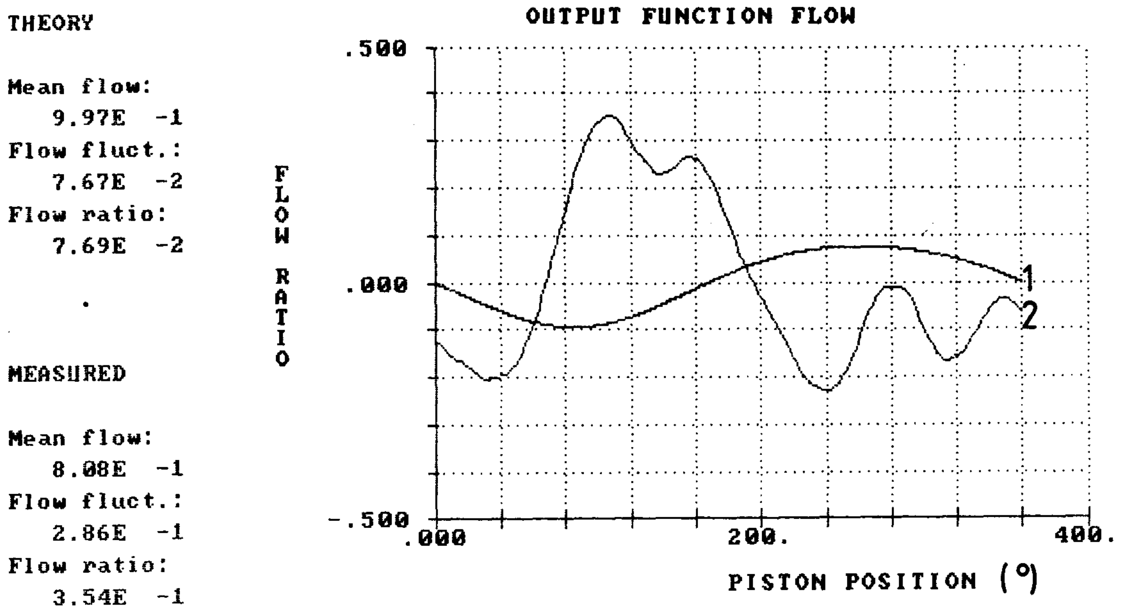


Figure 6.6 The course of the flow through the delivery line during one cycle of both the theoretical and the measured values. The data has been taken from experiment number 18, see table 6.1 .

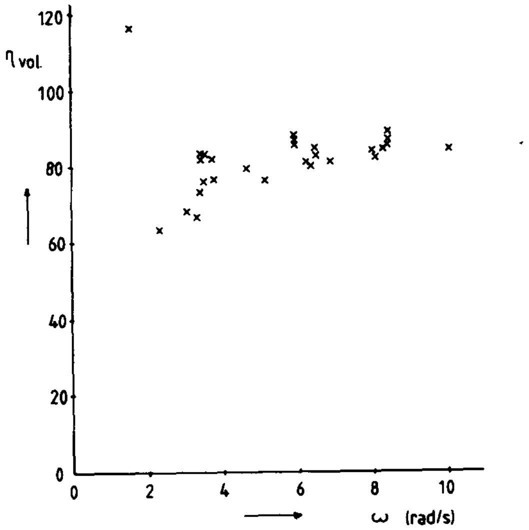


Figure 6.7 The volumetric efficiency as a function of the rotational speed.

## 6.4 THE HYDRODYNAMIC FORCE

The intention of the model was to describe the hydrodynamic force acting on the pump rod. We expected the delivery part to make the highest contribution to the hydrodynamic pump rod force. Thus there has to be a relationship between the course of the force in the pump rod and the pressure in the delivery airchamber.

The graphical results of experiment 18 are shown in fig. 6.8. The data of this experiment is to be found in table 6.1 . The graphs represent the pump rod force, the velocity of the pump rod, the flow through the delivery line and the pressure in the airchamber as functions of the piston position. The values in the upper right corner of each graph denote the static force on the pump rod (in N), the rotational speed of the pump rod (in rad/s), the mean flow (in $dm^3/s$) and the mean pressure (in bar) respectively.

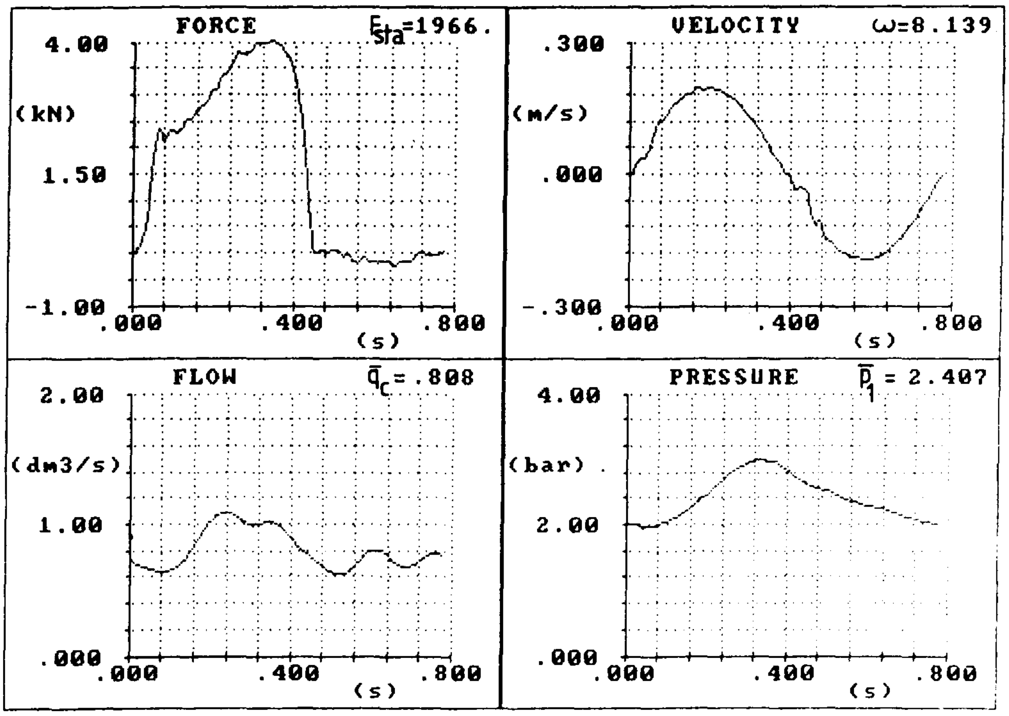
More graphical results are shown in Appendix 6C.

The difference between the maximum and the minimum pressure in the airchamber multiplied by the cross-section area of the piston should be about equal to the difference of the pump rod force between $\omega t \simeq 0.35$ rad and $\omega t \simeq 2.8$ rad, because the piston valve then is closed. For experiment 18 we find

$$(p_{max} - p_{min}) \cdot A_c \simeq 1 \cdot 10^5 * 1.54 \cdot 10^{-2} = 1.54 \text{ kN}$$

$$F_{2.8\ rad} - F_{0.35\ rad} \simeq 1.75 \text{ kN}$$

The difference of about 200 N might be the contribution of the suction part, the pump cylinder part and/or the pressure difference over the inlet of the delivery airchamber.



```
                          Mean flow:
Date: 09/30/86               8.08E  -1
Exp. number: 18           Flow fluct.:
No air supply.               2.86E  -1
Delivery head:            Flow ratio:
   1.00E  1                  3.54E  -1
                          Mean pressure:
Time one sample:             2.41E  0
   4.00E  0               Pressure fluct.:
Number of samp.:             5.76E  -1
         193              Pressure ratio:
                             2.39E  -1
```

Figure 6.8 The measured course of the pump rod force, the velocity of the pump rod, the flow through the delivery line and the pressure in the delivery airchamber during one cycle. The points .000 on the horizontal axes correspond to $\omega t=0$ (BDC). Other data are to be found in table 6.5 .

Also from the graphs in Appendix 6C one can see the influence of hydrodynamic effects on the pump rod force. Leaving the shock force out of consideration, the hydrodynamic force (mean value plus fluctuations) make the highest contribution to the pump rod force. This holds for our system in which $L_d$ and $R_d$ are large values compared with the delivery head $H_d$.

Although only one experiment has been analysed in detail, the expressions for the dimensionless pressure fluctuations (3.50) and (3.51) can be used as design rules for water pumping windmills. For example the designer don't want the dimensionless pressure fluctuations to be larger than 0.15 . After the expected mean pressure $\bar{p}_1$ is calculated, volume ratio $\nabla_s/\nabla_{atm}$ is imposed by the value 0.15 .

When air is supplied to the airchamber, the pressure fluctuations remain constant for all rotational speeds. Besides these fluctuations are smaller as is the case in which no air is supplied. The "air supply" method therefore will reduce the pump rod force more than the "no air supply" method will do.

# 7. CONCLUSIONS AND RECOMMENDATIONS

This chapter has been divided into two paragraphs. In the first paragraph the conlusions are given and in the second one some recommendations are given.
Both paragraphs has been subdivided into two parts. In the first part the conclusions (or recommendations) are given about the model, the measurements and the comparison between both. In the second part the new measuring system and especially the data acquisition unit is discussed.

## 7.1 CONCLUSIONS

### THE MODEL

The results from the model compare reasonably with the measurements as far as the pressure is concerned. This holds both for the amplitude and for the phase angle. The dimensionless pressure fluctuation $\Delta p_1/\overline{p}_1$ in the delivery airchamber is proportional to the volume ratio $\nabla_s/\nabla_{atm}$ and the pressure ratio $\overline{p}_1/p_{atm}$.

$$\frac{\Delta p_1}{\overline{p}_1} \sim \frac{\nabla_s}{\nabla_{atm}} \cdot \frac{\overline{p}_1}{p_{atm}} \tag{3.50}$$

If air is supplied to the (delivery) airchamber this expression simplifies to

$$\frac{\Delta p_1}{\overline{p}_1} \sim \frac{\nabla_s}{\nabla_{atm}} \tag{3.51}$$

So, if air is supplied, the dimensionless pressure fluctuation only depends on a volume ratio!

Hence the volume ratio $\nabla_s/\nabla_{atm}$ is an very important value, determining whether the pump rod force stays within bounds. Equations (3.50) and (3.51) can be used as a design rule for water pumping windmills. With a proper volume ratio less problems will arise with the failure of pump rods.

The maximum of the dimensionless pressure fluctuations is about 1.2 rad delayed compared with the maximum of the input signal $q_c$. Because the course of the pump rod force can be derived from the course of the pressure in the delivery airchamber, when the piston valve is closed, the maximum pump rod force caused by this pressure fluctuation therefore will be found at $\omega t \simeq 2.8$ rad $(1.2 + \pi/2)$.

It is not quite clear whether the difference between experimental and theoretical values for the flow fluctuations in a line is due to the inproper functioning of the flow meter or to inaccuracies of the model itself. Further investigation of the flow in and out of the airchamber is needed.

## THE NEW MEASUREMENT SYSTEM

The new data acquisition system operates satisfactorily. This new system certainly is an improvement compared to the old one. The measuring system now is more clearly layed out, data can be elaborated much faster and in a more accurate way, data can be stored for later use and more signals can be measured at the same time, so they can be compared which each other.
The software package Asyst offers many more possibilities than have been used up till now.

The new flow meter, the Speedmag of Endres & Hauser Flowtec, has not been a success up till now. Among other things problems have been arisen with earth contacts in the micro processor. At the moment of this writing Henk Oldenkamp, staff member of the WEG, is working on it.

## 7.2 RECOMMENDATIONS

### THE MODEL

The analysis of the measurements hasn't been performed entirely, due to a lack of time. Further elaboration is needed. This should be supplemented with other experiments, especially with other pumps, to obtain more certainty on the validity of the model.

The experiments with a constant air volume in the airchamber ("with air supply") indicate that this method keeps the pressure fluctuations in the system lower then when using a constant air mass in the airchamber ("no air supply").

When the flow meter has been repaired, the experiments should be repeated. At the same time this will check the reproducibility of the pressure measurements.

The shape of an airchamber and the position of it with respect to the piston propably are of great influence on the flow fluctuations in a line and hence on the pump rod forces.
If possible visual studies of the flow at the inlet of an airchamber should be performed. This will give more insight of the flow through the pump system and maybe makes it possible to explain the difference between the model and the flow measurements.

## THE NEW MEASURING SYSTEM

In the present situation, signals cannot be sampled in a shorter time than 2.5 ms per sample. With use of DMA (Direct Memory Access) the sample rate can be reduced to 60 $\mu$s (see Appendix 5A). High frecuency fluctuating signals like the shock force then can be better observed. Also the accuracy with which the rotational speed can be defined will improve.
One has to find an optimum between the sample rate and the number of samples needed to obtain at least one cycle.

It must be possible to trigger the measuring signals in such a way that the data acquisition board starts to sample at $\omega t=0$ (BDC). Averaging over the number of periods will improve the signal to noise ratio.

Another problem concerns the printer. Graphs can only be put on paper by a so-called screen dump to the printer. This execution takes a long time and besides the result is not very beautiful. An extension with a plotter would be an improvement.

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## APPENDIX 3A PRESSURE DIFFERENCES OVER A LINE

In our system, pressure differences are caused by

- the static head,
- the flow resistance and
- the acceleration of the water mass.

We want to know the pressure difference between the cross-sections 1 and 0 of fig. 3A.1.

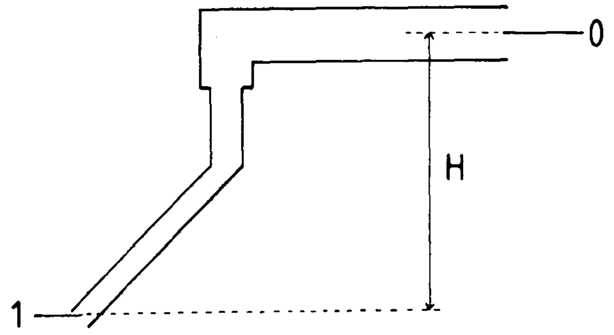


Figure 3A.1 A line showing different lengths and diameters.

### THE STATIC HEAD

The difference in height causes a static pressure difference.

$$(p_1 - p_0)_H = \rho g H \qquad (3A.1)$$

## THE FLOW RESISTANCE

The pressure loss over a pipe element is given by

$$(p_1-p_0)_R = f\cdot\frac{1}{2}\rho v^2 \qquad (3A.2)$$

in which f is a pressure loss coefficient and
v is the velocity of the water.

The pressure loss coefficient f can be split up into two parts. First there is a pressure loss due to the wall friction of a line.

$$f = \frac{\lambda\cdot l}{D}$$

in which $\lambda$ is the friction coefficient for pipe flow (in m/m),
l is the length of a line and
D is its diameter.

The second part consist of pressure losses due to bends, inlets, valves etc.

$$f = \sum_{i=1}^{n} \zeta_i$$

in which $\zeta$ is a pressure loss coefficient for a bend etc.

Because v equals q/A, where A is the cross-section of a line, we are able to reformulate (3A.2).

$$(p_1-p_0)_R = \frac{1}{2}\rho\cdot\left\{\sum_{i=1}^{n} \zeta_i\cdot\frac{1}{A_i{}^2} + \sum_{j=1}^{m} \frac{\lambda_j\cdot l_j}{D_j}\cdot\frac{1}{A_j{}^2}\right\}\cdot q^2 \qquad (3A.3)$$

Here the flow resistance R (in kg/m$^7$) is defined:

$$R = \frac{1}{2}\rho \cdot \left\{ \sum_{i=1}^{n} \zeta_i \cdot \frac{1}{A_i^2} + \sum_{j=1}^{m} \frac{\lambda_j \cdot l_j}{D_j} \cdot \frac{1}{A_j^2} \right\} \tag{3A.4}$$

This abbreviates (3A.3) to

$$(p_1 - p_0)_R = R \cdot q^2 \tag{3A.5}$$

## THE ACCELERATION OF THE WATER MASS

The acceleration of the mass of water also causes pressure differences in a line. This follows from Newton's law:

$$F = m \cdot a = m \cdot \dot{v}$$

$$(p_1 - p_0)_L \cdot A = \rho A l \cdot \frac{\dot{q}}{A}$$

$$(p_1 - p_0)_L = \frac{\rho l}{A} \cdot \dot{q} \tag{3A.6}$$

(A dot denotes a time derivative.)

We now define the line inertia L (in kg/m$^4$):

$$L = \frac{\rho l}{A}$$

If there are cross-sections of different sizes in a line, one can write a more general definition for L

$$L = \sum_{i=1}^{n} \frac{\rho l_i}{A_i} \tag{3A.7}$$

With definition (3A.7) equation (3A.6) becomes

$$(p_1-p_0)_L = L \cdot \dot{q} \tag{3A.8}$$

The total pressure difference $p_1-p_0$ is equal to the sum of eqs. (3A.1), (3A.5) and (3A.8).

$$p_1-p_0 = \rho g H + R \cdot q^2 + L \cdot \dot{q} \tag{3A.9}$$

## APPENDIX 3B THE TRANSFER FUNCTION

The amplitude and the phase angle of the transfer functions of eqs. (3.38) and (3.39) are complex functions of the rotational speed ratio $\omega/\omega_{syst}$ and the integer n of the Fourier series.

$$|H_n| = \sqrt{\frac{\left(\dfrac{\omega^2}{\omega_{syst}^2}\cdot\dfrac{R\omega_{syst}^2\cdot\nabla_s^2}{4\pi^2\cdot\bar{p}_1}\right)^2 + \left(n\cdot\dfrac{\omega^2}{\omega_{syst}^2}\cdot\dfrac{L\omega_{syst}^2\cdot\nabla_s}{2\pi\cdot\bar{p}_1}\right)^2}{\left(1 - n^2\cdot\dfrac{\omega^2}{\omega_{syst}^2}\cdot\dfrac{p_{sta}^2}{\bar{p}_1^2}\right)^2 + \left(n\cdot\dfrac{\omega^2}{\omega_{syst}^2}\cdot\dfrac{R\cdot\nabla_s}{2\pi\cdot L}\cdot\dfrac{p_{sta}^2}{\bar{p}_1^2}\right)^2}}$$

For the flow, the numerator equals 1 and the right-hand term in the denominator has to be multiplied by 2.

$$\phi_n = \arctan\left(\frac{n\cdot 2\pi\cdot L}{R\cdot\nabla_s}\right) - \arctan\left(\frac{n\cdot\dfrac{\omega^2}{\omega_{syst}^2}\cdot\dfrac{R\cdot\nabla_s}{2\pi\cdot L}\cdot\dfrac{p_{sta}^2}{\bar{p}_1^2}}{1 - n^2\cdot\dfrac{\omega^2}{\omega_{syst}^2}\cdot\dfrac{p_{sta}^2}{\bar{p}_1^2}}\right)$$

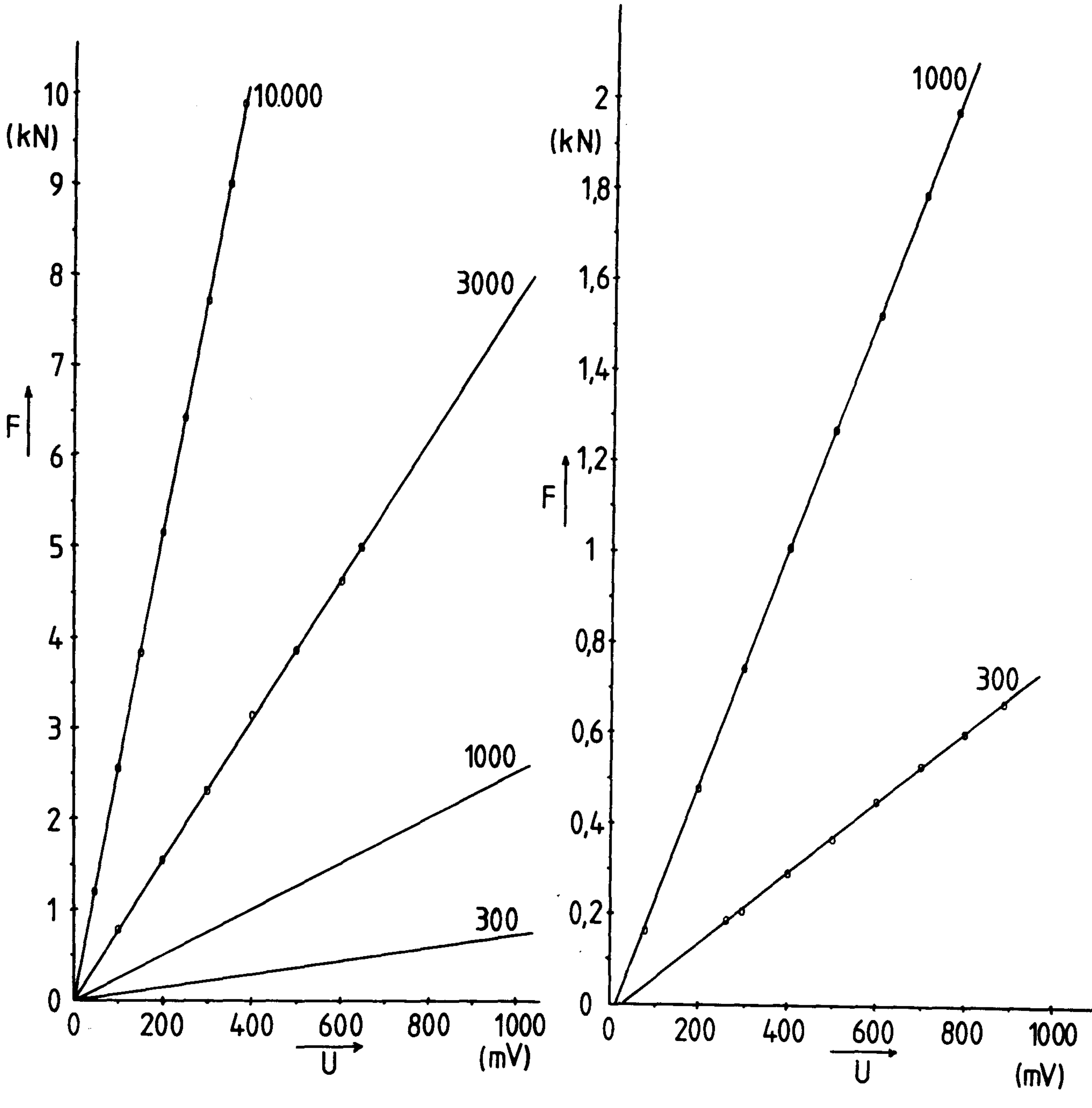
For the flow, the first arctan equals zero.

For $\bar{p}_1$ we write (see (3.40))

$$\bar{p}_1 = p_{sta} + \frac{R\cdot\nabla_s^2}{4\pi^2}\cdot\omega_{syst}^2\cdot\frac{\omega^2}{\omega_{syst}^2}$$

If air is supplied to the airchamber, the pressure ratio $\bar{p}_1/p_{sta}$ must be replaced by $\sqrt{(\bar{p}_1/p_{sta})}$, see par. 3.5 .

## APPENDIX 4A CALIBRATION CURVES OF THE STRAIN-GAUGE INDICATOR



Figures 4A.1 and 4A.2 The force on the strain-gauge as a function of the ouput voltage of the Peekel Transducer/Strainindicator. The values along the lines are the amplifier ranges of the Strainindicator. The divergence around zero is probably a wrong adjustment of the zero offset during the calibration measurements.

## APPENDIX 4B CALIBRATION CURVES OF THE PRESSURE TRANSDUCERS

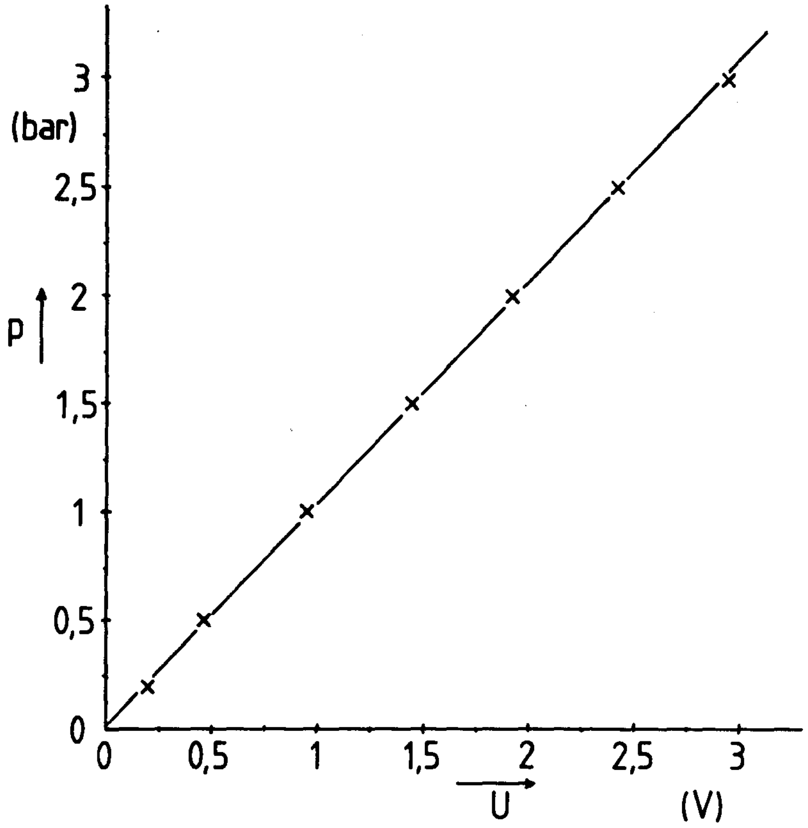


Figure 4B.1 The pressure on the pressure transducers as a function of the output voltage of the amplifier. The measured points of all three calibrated pressure transducers were so close to each other that only the calibration values of one transducer is drawn.

# APPENDIX 5A METRABYTE DASH-16 DATA ACQUISITION BOARD

Some extra information of the MetraByte Dash-16 data acquisition board is given below. The text is copied from the MetraByte Dash-16 Manual [13].

## 1.1 SUMMARY OF DASH-16 FUNCTIONS.

MetraByte's DASH-16 is a multifunction high speed analog/digital I/O expansion board for the IBM Personal Computer. It is a full length board that installs internally in an expansion slot of an IBM P.C. or P.C./XT[1] and turns the computer into a fast high precision data acquisition and signal analysis instrument. DASH-16 can also be used in buss compatible computers such as Compaq, Columbia, Zenith 150, Leading Edge, Corona etc. The board is of multilayer construction with integral ground plane to minimise noise and crosstalk at high frequencies. The following functions are implemented on the DASH-16:-

1. DASH-16 uses an industry standard (AD574A) 12 bit successive approximation converter with a 25 microsecond conversion time. The channel input configuration is switch selectable on the board, providing a choice between 16 single ended channels or 8 differential channels with 90dB common mode rejection and +/-10v common mode range. Throughput depends on the operating configuration:-

| Operating mode | Througput (conversions/sec) |
|---|---|
| Program transfer to simple variable | Up to 200 |
| Program transfer to array variable | " " 3000 |
| Interrupt driven transfer | " " 3000 |
| D.M.A. transfer on scan of channels | " " 25000 |
| D.M.A. transfer on single channel | " " 35000 |

The arrival of faster versions of the AD574A converter (AD674A, AD774A) will allow an upgrade of the speed in D.M.A. (direct memory access) mode by plug in replacement. The A/D may be triggered 3 ways, by software command, by internal programmable interval timer or by direct external trigger to the A/D and data may be transferred at the end of conversion in 3 ways, by program

---

[1] Registered trademark of International Business Machines Corporation.

transfer, by interrupt or by D.M.A. All operating modes are selected by a control register on the DASH-16 and supported by the software. For a block diagram of DASH-16, see Fig. 1.1.

2. High input impedance ranges of +1v, +2v, +5v & +10v unipolar and +/-0.5v, +/-1v, +/-2.5v, +/-5v & +/-10v bipolar are switch selectable. These ranges are common to all channels and are controlled by the gain of the input instrumentation amplifier. Other ranges may be realised with a single user installed resistor. All inputs are multiplexed through a low drift, fast settling instrumentation amplifier/sample-hold combination and the channel input configuration is switch selectable to operate as either 16 single ended or 8 differential channels.

3. A 3 channel programmable interval timer (Intel 8253) provides trigger pulses for the A/D at any rate from 250 KHz to 1 pulse/hr. 2 channels are operated in fixed divider configuration from an internal 1MHz xtal clock. The third channel is uncommitted and provides a gated 16 bit binary counter that can be used for event or pulse counting, delayed triggering, and in conjunction with the other channels for frequency and period measurement.

4. 2 channels of multiplying 12 bit D/A output. The D/A converters may be operated with a fixed -5v reference available from the DASH-16 board to give a 0 - +5v output. Alternatively an external D.C. or A.C. reference may be used to give different output ranges or programmable attenuator action on an A.C. signal. D/A's are double-buffered to provide instantaneous single step update.

5. A -5v (+/-0.05v) precision reference voltage output is derived from the A/D converter reference. Typical uses are providing a D.C. reference input for the D/A converters and offsets and bridge excitation to user supplied input circuits.

6. Digital I/O consists a 4 bits of TTL/DTL compatible digital output and 4 bits of digital input. Apart from being addressed as individual I/O ports, some of the digital inputs do double duty in some modes as A/D trigger and counter gate control inputs.

The following utility software for DASH-16 is provided on a single sided PC-DOS 1.10 format 5-1/4" floppy disk (upward compatible with DOS 2.0):-

1) A machine language driver (DASH16.BIN) for control of A/D, D/A and digital I/O channel functions and data transfer modes via BASIC CALL.
2) Programmable interval timer - setting pulse rate.
3) Initial setup and installation aids.
4) Graphical display of data versus time and x/y mode.
5) Calibration and test programs.

### 6) Examples and demonstration programs.

Using state of the art data conversion components, the DASH-16 has been designed to provide high data throughput using the D.M.A. capabilities of the IBM P.C. Direct memory access is the only satisfactory way of transferring data from the A/D to memory at rates above 10,000 samples sec. At this speed program transfers through the C.P.U. become difficult to handle in the short amount of time available and are also liable to disruption by other interrupt processes in the computer. Real time triggering of the A/D plus D.M.A. assures perfect synchronism in sampling unaffected by other computer operations. These capabilities are essential in applications such as signal analysis, fast fourier transform, vibration and transient analysis where high data rates must be sustained for short intervals of time. For slower applications where the added complexity of D.M.A. hardware is not required, MetraByte's DASH-8 or DASCON-1 data conversion boards are usually a more economical solution. DASH-16's open I/O mapped architecture together with 3 modes of data transfer, programmed via C.P.U., interrupt via C.P.U. and D.M.A. via D.M.A. controller provides considerable flexibility in application.

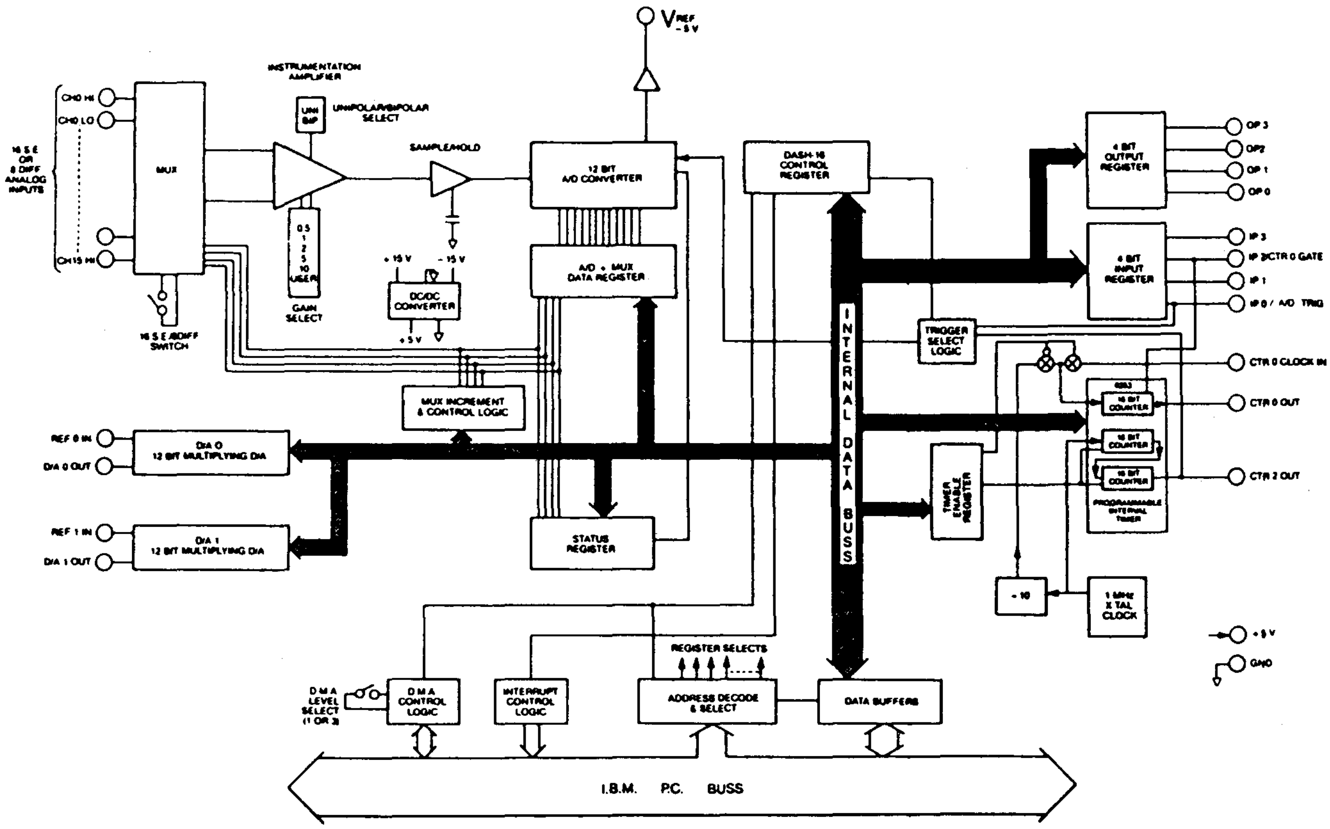


Fig. 1.1 BLOCK DIAGRAM OF DASH-16

## APPENDIX 5B LISTING OF THE COMPUTER PROGRAMS

The listing of the following computer programs is given:

| | |
|---|---|
| - PUMP.TXT | In this program text is given corresponding with pump data. Used in the functions PRINT DATA ON SCREEN/PRINTER. |
| - PUMP.DAT | In this program pump data are stored and calculated. These data are automatically stored together with measured data when using WRITE DATA. Also used in several other functions. |
| - INSTALL.DMO | In this program the size of the arrays in which the measured data are to be stored in and the configuration of the MetraByte board are installed. Used in CHANGE OPTIONS. |
| - MEASURE.DMO | This is the main program. Comments are included to describe different functions. A User's Guide of this program is given in Appendix 5C. |
| - COMPARE.DAT | The measured data are compared with the theoretical model of Chapter 3. This program first has to be loaded before the function PLOT FLOW and PLOT PRESSURE can be used. |

```
IM[ 4 , 9 ] STRING.ARRAY SUPERSCRIPT
IM[ 4 , 9 ] STRING.ARRAY SUBSCRIPT
IM[ 12 , 13 ] STRING.ARRAY PUMPINFO.1
IM[ 12 , 16 ] STRING.ARRAY PUMPINFO.2

 SUCTION " SUPERSCRIPT "[ 1 ] ":=
DELIVERY " SUPERSCRIPT "[ 2 ] ":=
  PUMP   " SUPERSCRIPT "[ 3 ] ":=
 GENERAL " SUPERSCRIPT "[ 4 ] ":=

MEAN FLOW" SUBSCRIPT "[ 1 ] ":=
FLOW FLUC" SUBSCRIPT "[ 2 ] ":=
MEAN PRES" SUBSCRIPT "[ 3 ] ":=
PRES FLUC" SUBSCRIPT "[ 4 ] ":=

STROKE         " PUMPINFO.1 "[ 1 ] ":=
AIRCH/STR VOL" PUMPINFO.1 "[ 2 ] ":=
LENGTH         " PUMPINFO.1 "[ 3 ] ":=
DIAMETER       " PUMPINFO.1 "[ 4 ] ":=
CROSS-SECTION" PUMPINFO.1 "[ 5 ] ":=
HEAD           " PUMPINFO.1 "[ 6 ] ":=
LAMBDA         " PUMPINFO.1 "[ 7 ] ":=
CHI            " PUMPINFO.1 "[ 8 ] ":=
R              " PUMPINFO.1 "[ 9 ] ":=
L              " PUMPINFO.1 "[ 10 ] ":=
Csystem        " PUMPINFO.1 "[ 11 ] ":=
wsystem        " PUMPINFO.1 "[ 12 ] ":=

RO WATER          " PUMPINFO.2 "[ 1 ] ":=
ATM PRESSURE      " PUMPINFO.2 "[ 2 ] ":=
GAS CONSTANT      " PUMPINFO.2 "[ 3 ] ":=
RANGE FORCE Tr/S" PUMPINFO.2 "[ 4 ] ":=
RANGE FLOW Trans" PUMPINFO.2 "[ 5 ] ":=
TOTAL HEAD        " PUMPINFO.2 "[ 6 ] ":=
STATIC FORCE      " PUMPINFO.2 "[ 7 ] ":=
ONE SAMPLE (ms.)" PUMPINFO.2 "[ 8 ] ":=
NUMBER SAMPLES    " PUMPINFO.2 "[ 9 ] ":=
                  " PUMPINFO.2 "[ 10 ] ":=
AIR SUPPLY        " PUMPINFO.2 "[ 11 ] ":=
ROTATIONAL SPEED" PUMPINFO.2 "[ 12 ] ":=




SYST Version 1.51
age 1     a:pump.txt   09/25/86    12:52
```

```
REAL DIM[ 1 ] ARRAY DUMMY
REAL DIM[ 13 , 4 ] ARRAY PUMPCHAR
0 PUMPCHAR :=

INTEGER SCALAR NUMBER.SAMPLES
REAL SCALAR RO.WATER       1.00E+03 RO.WATER :=
SCALAR P.ATM               1.01E+05 P.ATM :=
SCALAR GAS.CONST           1.40E+00 GAS.CONST :=
SCALAR F.RANGE
SCALAR Q.RANGE
SCALAR HEAD
SCALAR F.STATIC
SCALAR ONE.SAMPLE
SCALAR AIR.SUPPLY          0.00E+00 AIR.SUPPLY :=
SCALAR OMEGA
SCALAR D.AIRCH.H           5.20E-01 D.AIRCH.H :=
SCALAR STROKE              5.00E-02 STROKE :=
SCALAR S.AIRCH.VOL         3.40E-03 S.AIRCH.VOL :=
SCALAR D.AIRCH.VOL         4.79E-03 D.AIRCH.VOL :=
SCALAR STROKE.VOL
SCALAR S.LENGTH            7.50E+00 S.LENGTH :=
SCALAR D.LENGTH            1.04E+02 D.LENGTH :=
SCALAR P.LENGTH            9.00E-01 P.LENGTH :=
SCALAR S.DIAM              5.30E-02 S.DIAM :=
SCALAR D.DIAM              3.59E-02 D.DIAM :=
SCALAR P.DIAM              1.40E-01 P.DIAM :=
SCALAR S.CR-SECT
SCALAR D.CR-SECT
SCALAR P.CR-SECT
SCALAR S.HEAD              1.85E+00 S.HEAD :=
SCALAR D.HEAD              0.00E+00 D.HEAD :=
SCALAR P.HEAD              0.90E+00 P.HEAD :=
SCALAR S.LAMBDA            2.90E-02 S.LAMBDA :=
SCALAR D.LAMBDA            2.90E-02 D.LAMBDA :=
SCALAR P.LAMBDA            3.00E-02 P.LAMBDA :=
SCALAR S.CHI               1.00E+00 S.CHI :=
SCALAR D.CHI               5.00E+00 D.CHI :=
SCALAR P.CHI               3.94E+01 P.CHI :=
SCALAR S.R
SCALAR D.R
SCALAR P.R
SCALAR S.L
SCALAR D.L
SCALAR P.L
SCALAR S.Csyst
SCALAR D.Csyst
SCALAR S.wsyst
SCALAR D.wsyst
SCALAR Q.MEAN
SCALAR DELTA.Q
SCALAR P.MEAN
SCALAR DELTA.P

: PUMP.CALCULATE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```

```
    0.90 0.52 + D.AIRCH.H - P.HEAD :=
    S.HEAD D.HEAD + P.HEAD + HEAD :=
    S.DIAM 2 ** PI * 4 / S.CR-SECT :=
    D.DIAM 2 ** PI * 4 / D.CR-SECT :=
    P.DIAM 2 ** PI * 4 / P.CR-SECT :=
    9810 HEAD * P.CR-SECT * F.STATIC :=
    .140 2 ** .0887 2 ** - PI * 4 / D.AIRCH.H * D.AIRCH.VOL :=
    STROKE P.CR-SECT * STROKE.VOL :=
    .5 RO.WATER * S.CHI S.LAMBDA S.LENGTH * S.DIAM / + * S.CR-SECT 2 ** /
    S.R :=
    .5 RO.WATER * D.CHI D.LAMBDA D.LENGTH * D.DIAM / + * D.CR-SECT 2 ** /
    D.R :=
    .5 RO.WATER * P.CHI * P.CR-SECT 2 ** / P.R :=
    RO.WATER S.LENGTH * S.CR-SECT / S.L :=
    RO.WATER D.LENGTH * D.CR-SECT / D.L :=
    9.42E+04 P.L :=
    AIR.SUPPLY 0 =
    IF
    P.ATM S.AIRCH.VOL * GAS.CONST / P.ATM 9810 S.HEAD * + 2 ** / S.Csyst :=
    P.ATM D.AIRCH.VOL * GAS.CONST / P.ATM 9810 D.HEAD * + 2 ** / D.Csyst :=
    ELSE
    S.AIRCH.VOL GAS.CONST / P.ATM 9810 S.HEAD * + / S.Csyst :=
    D.AIRCH.VOL GAS.CONST / P.ATM 9810 D.HEAD * + / D.Csyst :=
    THEN
    S.Csyst S.L * -.5 ** S.wsyst :=
    D.Csyst D.L * -.5 ** D.wsyst :=
;

: PUMPDATA
    RO.WATER       PUMPCHAR [ 1 , 4 ] :=
    P.ATM          PUMPCHAR [ 2 , 4 ] :=
    GAS.CONST      PUMPCHAR [ 3 , 4 ] :=
    F.RANGE        PUMPCHAR [ 4 , 4 ] :=
    Q.RANGE        PUMPCHAR [ 5 , 4 ] :=
    HEAD           PUMPCHAR [ 6 , 4 ] :=
    F.STATIC       PUMPCHAR [ 7 , 4 ] :=
    ONE.SAMPLE     PUMPCHAR [ 8 , 4 ] :=
    NUMBER.SAMPLES PUMPCHAR [ 9 , 4 ] :=
    AIR.SUPPLY     PUMPCHAR [ 11 , 4 ] :=
    OMEGA          PUMPCHAR [ 12 , 4 ] :=
    D.AIRCH.H      PUMPCHAR [ 1 , 2 ] :=
    STROKE         PUMPCHAR [ 1 , 3 ] :=
    S.AIRCH.VOL    PUMPCHAR [ 2 , 1 ] :=
    D.AIRCH.VOL    PUMPCHAR [ 2 , 2 ] :=
    STROKE.VOL     PUMPCHAR [ 2 , 3 ] :=
    S.LENGTH       PUMPCHAR [ 3 , 1 ] :=
    D.LENGTH       PUMPCHAR [ 3 , 2 ] :=
    P.LENGTH       PUMPCHAR [ 3 , 3 ] :=
    S.DIAM         PUMPCHAR [ 4 , 1 ] :=
    D.DIAM         PUMPCHAR [ 4 , 2 ] :=
    P.DIAM         PUMPCHAR [ 4 , 3 ] :=
    S.CR-SECT      PUMPCHAR [ 5 , 1 ] :=
    D.CR-SECT      PUMPCHAR [ 5 , 2 ] :=
    P.CR-SECT      PUMPCHAR [ 5 , 3 ] :=
```

```
    S.HEAD         PUMPCHAR [ 6 , 1 ] :=
    D.HEAD         PUMPCHAR [ 6 , 2 ] :=
    P.HEAD         PUMPCHAR [ 6 , 3 ] :=
    S.LAMBDA       PUMPCHAR [ 7 , 1 ] :=
    D.LAMBDA       PUMPCHAR [ 7 , 2 ] :=
    P.LAMBDA       PUMPCHAR [ 7 , 3 ] :=
    S.CHI          PUMPCHAR [ 8 , 1 ] :=
    D.CHI          PUMPCHAR [ 8 , 2 ] :=
    P.CHI          PUMPCHAR [ 8 , 3 ] :=
    S.R            PUMPCHAR [ 9 , 1 ] :=
    D.R            PUMPCHAR [ 9 , 2 ] :=
    P.R            PUMPCHAR [ 9 , 3 ] :=
    S.L            PUMPCHAR [ 10 , 1 ] :=
    D.L            PUMPCHAR [ 10 , 2 ] :=
    P.L            PUMPCHAR [ 10 , 3 ] :=
    S.Csyst        PUMPCHAR [ 11 , 1 ] :=
    D.Csyst        PUMPCHAR [ 11 , 2 ] :=
    S.wsyst        PUMPCHAR [ 12 , 1 ] :=
    D.wsyst        PUMPCHAR [ 12 , 2 ] :=
    Q.MEAN         PUMPCHAR [ 13 , 1 ] :=
    DELTA.Q        PUMPCHAR [ 13 , 2 ] :=
    P.MEAN         PUMPCHAR [ 13 , 3 ] :=
    DELTA.P        PUMPCHAR [ 13 , 4 ] :=
;

: PUMPDATA.IN
    PUMP.CALCULATE
    PUMPDATA
;
```

```
 Install scalars in execution variables
NSTALL ONE.SAMPLE IN FREQ
NSTALL NUMBER.SAMPLES IN SAMPLES

NTEGER DIM[ SAMPLES , 4 ] ARRAY ALL.SIGNALS
EAL DIM[ SAMPLES ] ARRAY SIGNAL
EAL DIM[ SAMPLES ] ARRAY TIME
IME []RAMP                          \ Fill array TIME with values 1 to SAMPLES
IME 1000 / FREQ * TIME :=

 Install arrays in execution variables
NSTALL ALL.SIGNALS IN ALL.S
NSTALL SIGNAL IN S
NSTALL TIME IN T

 Initiate the first 4 channels on the data-acquisition interface card and make
 array ALL.SIGNALS a buffer array to store the data of the signals.
 3 A/D.TEMPLATE ALL.CHANNELS
L.SIGNALS TEMPLATE.BUFFER
/D.INIT

 Install template in execution variables
NSTALL ALL.CHANNELS IN CHNLS
```

```
\ This program is designed to collect data of transducers connected to a pump
\ in the pump test rig.
\ The frequency to sample the signals of the transducers can be chosen just as
\ the number of samples.
\ The measured signals can be presented in numbers and/or in graphics on your
\ screen and/or on a printer. The program gives the possibility to write the
\ data to a floppy disk and to read stored data from it.
\
\ The program is menu driven and so can be used without prior knowledge of
\ Asyst.

\ Introduce execution variables
XEQ FREQ                 \ Execution variable for sample rate
XEQ SAMPLES              \      "         "     for the number of samples
XEQ ALL.S                \      "         "     for the array ALL.SIGNALS
XEQ S                    \      "         "            "        SIGNAL
XEQ T                    \      "         "            "        TIME
XEQ CHNLS                \      "         "     for the template
XEQ GOBACK.MAIN          \      "         "     for the procedure MAIN.PROGRAM
XEQ PLOT.Q.THEORY        \      "         "     for the procedure PLOT.FLOW
XEQ PLOT.P.THEORY        \      "         "     for the procedure PLOT.PRESSURE

\ Introduce scalars
INTEGER SCALAR EXP#      \ Experiment number
SCALAR SIGN.NUMB         \ Number of the signal on the data acquisition board

REAL SCALAR A/D.ZERO     \ The value of the bit which stands for zero Volt
SCALAR Y.MAX             \ The maximum value of the y-axis
SCALAR Y.MIN             \ The minimum    "     "
SCALAR MID               \ The mean value of a signal

\ Introduce strings
 3 STRING STR.EXP#       \ String for the experiment number
.5 STRING MEAS.SIGN      \ Name of the measured signal (force etc.)
 9 STRING DIM.LABEL      \ Dimension of the measured signal
 6 STRING EXTRA.INFO     \ Label for extra information
:4 STRING FILENAME       \ Name of file to write or to read

\ Lay-out of the windows
 0  0    0  79   WINDOW {TOPLINE}   \ Top banner line across screen
 1  0   24  79   WINDOW {TOT-TOP}   \ Whole screen except top line
.4  0   23  79   WINDOW {MENU}      \ Middle window for menu's
:4  0   24  79   WINDOW {BOTLINE}   \ Bottom line for messages
 0  0   23  17   WINDOW {COMM}      \ Left window for comments

\ Place a banner in the top line of the screen
 TOP.LINE
   {TOPLINE} SCREEN.CLEAR
   16 SPACES ." ==   Pump Data Measuring & Plotting Program   =="


\ Place a message in the bottom line of the screen
 BOTTOM.LINE.CHOICE
   {BOTLINE} SCREEN.CLEAR
```

```
    ."   Your choice ?"
;

\ Show the function of each function key in the Main Program
: MAIN.MENU
    GRAPHICS.DISPLAY
    TOP.LINE
    {TOT-TOP} SCREEN.CLEAR
    {MENU} SCREEN.CLEAR
    30 SPACES ." ==   Main Menu   ==" CR CR CR
     7 SPACES ." F1"
    14 SPACES ." F2"
    14 SPACES ." F3"
    14 SPACES ." F4"
    14 SPACES ." F5" CR
     4 SPACES ." MEASURE           DIR"
     9 SPACES ." WRITE FILE     READ FILE"
     5 SPACES ." CHANGE OPTIONS" CR CR
     7 SPACES ." F6"
    14 SPACES ." F7"
    14 SPACES ." F8"
    14 SPACES ." F9"
    14 SPACES ." F10" CR
     6 SPACES ." PLOT          PRINT DATA        SMOOTH"
     7 SPACES ." LEAVE PROGRAM    LEAVE ASYST"
    BOTTOM.LINE.CHOICE
;

: BOTTOM.LINE.MAIN
    {BOTLINE} SCREEN.CLEAR
    ." Press any key to go back to the MAIN MENU."
    PCKEY ?DROP DROP
    MAIN.MENU
;

\ Measure the signals on the channels 0 to 3
: GET.SIGNALS
    SYNC.PERIOD
    CHNLS A/D.INIT                  \ Initiate data acquisition board
    BEGIN
       SYNCHRONIZE                  \ Take a sample every given sample time
       A/D.IN>ARRAY                 \ Store the signals into the buffer array
       ?BUFFER.FULL                 \ until it is full
    UNTIL
    ?SYNC.LATE
    IF
         ." Time for one sample is too small!!" BELL BELL
    THEN
;

: MEASURE
    {MENU} SCREEN.CLEAR
    FREQ                            \ Time needed for one sample
    GET.SIGNALS
```

```
   EXP# 1 + EXP# :=
   EXP# "." STR.EXP# ":=
   MAIN.MENU


Give a list of the files on your disk in drive b.
DIRECTORY
   {TOT-TOP} SCREEN.CLEAR CR CR
   DIR B:
   BOTTOM.LINE.MAIN


GET.FILENAME
   ." Filename please? (Max. 15 characters)  " "INPUT FILENAME ":=
   " B:" FILENAME "CAT FILENAME ":=
   {TOT-TOP} SCREEN.CLEAR CR CR


Make room for a file to save on disk and write the measured data into
the file
WRITE.DATA.FILE
   FILE.TEMPLATE
        1 COMMENTS
        REAL DIM[ SAMPLES , 4 ] SUBFILE
        REAL DIM[ SAMPLES ] SUBFILE
        REAL DIM[ 13 , 4 ] SUBFILE
   END
   ." Opening file " FILENAME "TYPE
   FILENAME DEFER> FILE.CREATE CR
   ." Writing file " FILENAME "TYPE
   FILENAME DEFER> FILE.OPEN CR
   STR.EXP#   1 >COMMENT
   1 SUBFILE ALL.S     ARRAY>FILE
   2 SUBFILE T         ARRAY>FILE
   3 SUBFILE PUMPCHAR  ARRAY>FILE
   FILE.CLOSE
ERR:
   CR ." Can't open file for writing. "  CR    \ For example when your disk
   ." Type any key to continue. "  BELL        \ is full
   PCKEY ?DROP DROP
   ?FILE.OPEN
   IF
        FILE.CLOSE
   THEN


OUTPUT.DATA.FILE
   PUMPDATA.IN
   {TOT-TOP} SCREEN.CLEAR CR CR
   ." Output "
   GET.FILENAME
   WRITE.DATA.FILE
   MAIN.MENU
```

```
: COMPARE.SAMPLES
     1 COMMENT> STR.EXP# ":=
     3 SUBFILE PUMPCHAR  FILE>ARRAY
     NUMBER.SAMPLES PUMPCHAR [ 9 , 4 ] =
     IF
          PUMPCHAR [ 9 , 4 ] NUMBER.SAMPLES :=
     ELSE
          PUMPCHAR [ 9 , 4 ] NUMBER.SAMPLES :=
          LOAD A:INSTALL.DMO
     THEN
     1 SUBFILE ALL.S     FILE>ARRAY
     2 SUBFILE T         FILE>ARRAY
;

\ Read file of stored data
: READ.DATA.FILE
     ." Reading file " FILENAME DEFER> FILE.OPEN
     FILENAME "TYPE CR
     COMPARE.SAMPLES
     PUMPCHAR [ 1 , 2 ] D.AIRCH.H :=
     PUMPCHAR [ 1 , 3 ] STROKE :=
     PUMPCHAR [ 4 , 4 ] F.RANGE :=
     PUMPCHAR [ 5 , 4 ] Q.RANGE :=
     PUMPCHAR [ 6 , 2 ] D.HEAD :=
     PUMPCHAR [ 8 , 4 ] ONE.SAMPLE :=
     PUMPCHAR [ 11 , 4 ] AIR.SUPPLY :=
     PUMPCHAR [ 12 , 4 ] OMEGA :=
     PUMPCHAR [ 13 , 1 ] Q.MEAN :=
     PUMPCHAR [ 13 , 2 ] DELTA.Q :=
     PUMPCHAR [ 13 , 3 ] P.MEAN :=
     PUMPCHAR [ 13 , 4 ] DELTA.P :=
     FILE.CLOSE
ONERR:
     CR ." Can't open file for writing. "  CR
     ." Type any key to continue. "  BELL
     PCKEY ?DROP DROP
     ?FILE.OPEN
     IF
          FILE.CLOSE
     THEN
;

: INPUT.DATA.FILE
     {TOT-TOP} SCREEN.CLEAR CR CR
     ." Input "
     GET.FILENAME
     READ.DATA.FILE
     MAIN.MENU
;

: CHANGE.OPTIONS
     {TOT-TOP} SCREEN.CLEAR CR CR
     ." Time needed for one sample (in ms.): " #INPUT ONE.SAMPLE := CR
```

```
  ." Number of samples: " #INPUT NUMBER.SAMPLES := CR
  ." Range of Transducer/Strainindicator: " #INPUT F.RANGE := CR
  ." Measuring range of flowmeter: " #INPUT Q.RANGE := CR
  ." Delivery head: " #INPUT D.HEAD := CR
  ." Stroke: " #INPUT STROKE := CR
  ." Height airchamber at atmospheric pressure: " #INPUT D.AIRCH.H := CR
  ." Air supply (0=without , 1=with): " #INPUT AIR.SUPPLY := CR
  PUMPDATA.IN
  LOAD A:INSTALL.DMO
  MAIN.MENU


Show the function of each function key in the Plot & Print Program
PLOT&PRINT.MENU
  GRAPHICS.DISPLAY
  TOP.LINE
  {TOT-TOP} SCREEN.CLEAR
  {MENU} SCREEN.CLEAR
  26 SPACES ." ==   Plot & Print  Menu   ==" CR CR CR
   7 SPACES ." F1"
  14 SPACES ." F2"
  14 SPACES ." F3"
  14 SPACES ." F4"
  14 SPACES ." F5" CR
   1 SPACES ." PLOT 1 SIGNAL   PLOT 4 SIGNALS"
  20 SPACES ." PLOT FLOW     PLOT PRESSURE" CR CR   \ These are theory plots
   7 SPACES ." F6"
  14 SPACES ." F7"
  14 SPACES ." F8"
  14 SPACES ." F9"
  14 SPACES ." F10" CR
   3 SPACES ." MAIN MENU       PRINT DATA      PRINT DATA"
   4 SPACES ." LEAVE PROGRAM    LEAVE ASYST" CR
  19 SPACES ." ON SCREEN       ON PRINTER"
  BOTTOM.LINE.CHOICE


BOTTOM.LINE.PLOT&PRINT
  {BOTLINE} SCREEN.CLEAR
  ." Press RETURN to go back to the PLOT&PRINT MENU."
  PCKEY ?DROP DROP
  PLOT&PRINT.MENU


Smooth the signals to reduce the noise
SMOOTH.SIGNALS
  {MENU} SCREEN.CLEAR
  .25 SET.CUTOFF.FREQ
  ALL.S XSECT[ ! , 1 ] SMOOTH ALL.S XSECT[ ! , 1 ] :=
  ALL.S XSECT[ ! , 2 ] SMOOTH ALL.S XSECT[ ! , 2 ] :=
  ALL.S XSECT[ ! , 3 ] SMOOTH ALL.S XSECT[ ! , 3 ] :=
  ALL.S XSECT[ ! , 4 ] SMOOTH ALL.S XSECT[ ! , 4 ] :=
  MAIN.MENU
```

```
\ Leave this program but remain in Asyst
: LEAVE.PROGRAM
    {TOT-TOP} SCREEN.CLEAR CR CR
    ." Type <ctrl-Break> to go back to ASYST. " CR
    ." Any other key takes you back to the Main Menu. "
    PCKEY ?DROP DROP
    MAIN.MENU
;

: LEAVE.ASYST
    {TOT-TOP} SCREEN.CLEAR CR CR
    ." Type Y if you want to leave ASYST. " CR
    ." Any other key takes you back to the Main Menu. "
    PCKEY ?DROP 89 =
    IF
         BYE
    THEN
    MAIN.MENU
;

: BOTTOM.LINE.WHICH
    ." Which signal must be plotted? (0,1,2,3): "
    #INPUT SIGN.NUMB :=
    SIGN.NUMB 1 + SIGN.NUMB := CR
;

: BOTTOM.LINE.WHAT
    ." What kind of signal is this? (FORCE,PRESSURE,...): "
    "INPUT MEAS.SIGN ":= CR
;

\ Convert the values of the signals from bit into Newtons etc.
\ Label the graphics with information about the signal
: AXIS.SCALE
    ALL.S XSECT[ ! , 2 ] S :=
    S []MAX S []MIN + 2 / A/D.ZERO :=
    ALL.S XSECT[ ! , SIGN.NUMB ] S :=
    " FORCE" MEAS.SIGN "WITHIN                      \ When the signal is a force
    IF
         PUMPCHAR [ 4 , 4 ] F.RANGE :=
         PUMPCHAR [ 7 , 4 ] F.STATIC :=
         " (kN)" DIM.LABEL ":=                      \ Put the dimension of the
         S A/D.ZERO - 204.75 / S :=                 \ signal in a label
         F.RANGE 300 =
         IF
              S .789 * S :=
              F.STATIC "." EXTRA.INFO ":=           \ Write the value of the static
              2.5 Y.MAX :=                          \ force in a label
             -2.5 Y.MIN :=
         ELSE
              F.RANGE 1000 =
              IF
                   S 2.61 * S :=
```

```
               F.STATIC "." EXTRA.INFO ":=
               2.5 Y.MAX :=
              -2.5 Y.MIN :=
          ELSE
               F.RANGE 3000 =
               IF
                    S 7.77 * S :=
                    F.STATIC "." EXTRA.INFO ":=
                    5 Y.MAX :=
                   -5 Y.MIN :=
               ELSE
                    F.RANGE 10000 =
                    IF
                         S 25.9 * S :=
                         F.STATIC "." EXTRA.INFO ":=
                         10 Y.MAX :=
                        -10 Y.MIN :=
                    THEN
               THEN
          THEN
     THEN
ELSE
     " PRESSURE" MEAS.SIGN "WITHIN
     IF
          " (bar)" DIM.LABEL ":=
          S A/D.ZERO - 204.75 / S :=
          S []MAX S []MIN + 2 / MID :=
          S MID - S :=
          S []MAX S []MIN - 2 / DELTA.P :=
          MID P.ATM 1.E+05 / + P.MEAN :=
          P.MEAN "." EXTRA.INFO ":=
          DELTA.P 0.5 <
          IF
               0.5  Y.MAX :=
              -0.5  Y.MIN :=
          ELSE
               1.0  Y.MAX :=
              -1.0  Y.MIN :=
          THEN
     ELSE
          " VELOCITY" MEAS.SIGN "WITHIN
          IF
               " (m/s)" DIM.LABEL ":=
               S A/D.ZERO - 204.75 / .125 * S :=
               S []MAX S []MIN - STROKE / OMEGA :=
               OMEGA "." EXTRA.INFO ":=
               S []MAX .125 <
               IF
                   .125 Y.MAX :=
                  -.125 Y.MIN :=
               ELSE
                   .250 Y.MAX :=
                  -.250 Y.MIN :=
               THEN
```

```
               ELSE
                    " FLOW" MEAS.SIGN "WITHIN
                    IF
                         PUMPCHAR [ 5 , 4 ] Q.RANGE :=
                         " (dm3/s)" DIM.LABEL ":=
                         S A/D.ZERO - 2047.5 / Q.RANGE * S :=
                         S []MAX S []MIN + 2 / Q.MEAN :=
                         S Q.MEAN - S :=
                         S []MAX S []MIN - 2 / DELTA.Q :=
                         Q.MEAN "." EXTRA.INFO ":=
                         DELTA.Q 0.5 <
                         IF
                              0.5  Y.MAX :=
                             -0.5  Y.MIN :=
                         ELSE
                              1.0  Y.MAX :=
                             -1.0  Y.MIN :=
                         THEN
                    THEN
               THEN
          THEN
     THEN
;

: BEGIN.PLOT.SIGNAL
     BOTTOM.LINE.WHICH
     BOTTOM.LINE.WHAT
     AXIS.SCALE
;

\ Full screen vuport for data plotting
: VU.1
     .25  .10     VUPORT.ORIG               \ Bottom left corner of the vuport
     .80  .80     VUPORT.SIZE               \ Size of the vuport
;

\ Upper left vuport for data plotting
: VU.4.1
     .25  .55     VUPORT.ORIG
     .375 .45     VUPORT.SIZE
;

\ Upper right vuport for data plotting
: VU.4.2
     .625 .55     VUPORT.ORIG
     .375 .45     VUPORT.SIZE
;

\ Lower left vuport for data plotting
: VU.4.3
     .25  .10     VUPORT.ORIG
     .375 .45     VUPORT.SIZE
;
```

```
Lower right vuport for data plotting
VU.4.4
   .625 .10     VUPORT.ORIG
   .375 .45     VUPORT.SIZE


Vuport lay-out
SIGNAL.VU
   HORIZONTAL  AXIS.ON                  \ Draw axis
   0 5 LABEL.POINTS                     \ Write a value each fifth point
   VERTICAL    AXIS.ON                  \ beginning at zero
   0 5 LABEL.POINTS
   .25  .15     AXIS.ORIG
   .65  .75     AXIS.SIZE
   .025 .008    TICK.SIZE               \ Lay-out of the numbers along the axes
   .5   .8      TICK.JUST


Axis lay-out
SIGNAL.VU.SET
   WORLD.COORDS                         \ Coordinates of the signals
   Y.MIN  Y.MAX  VERTICAL   WORLD.SET   \ Minimum and maximum value of the
   0    T []MAX  HORIZONTAL WORLD.SET   \ horizontal and vertical axis
   NORMAL.COORDS
   .25     .15    AXIS.POINT
   XY.AXIS.PLOT                         \ Plot axes and numbers along them
   OUTLINE                              \ Draw a rectangular around the vuport


Label plotting
SIGNAL.LABEL
   GRAPHICS.READOUT
   NORMAL.COORDS
   .80    .95  POSITION
   EXTRA.INFO   LABEL
   .72    .05  POSITION
   " (s)"      LABEL
   .35    .95  POSITION
   MEAS.SIGN   LABEL
   .025   .70  POSITION
   DIM.LABEL    LABEL


END.PLOT.SIGNAL
   SIGNAL.VU
   SIGNAL.VU.SET
   T  S  XY.DATA.PLOT
   SIGNAL.LABEL


Put the comments to the graphics in the {COMM} window
SHOW.COMMENTS.GENERAL
   {COMM} SCREEN.CLEAR
   ." Date: " .DATE   CR
```

```
     ." Exp. number:"          1 SPACES STR.EXP# "TYPE CR
     PUMPCHAR [ 11 , 4 ] 0 =
     IF
         ." No air supply." CR
     ELSE
         ." With air supply." CR
     THEN
     9. 2. SCI.FORMAT                       \ Write numbers in scientific notation
     ." Delivery head:"    CR 3 SPACES PUMPCHAR [ 6 , 2 ] . CR CR
     ." Time one sample:"  CR 3 SPACES PUMPCHAR [ 8 , 4 ] . CR
     ." Number of samp.:"  CR 3 SPACES SAMPLES . CR CR
;

: SHOW.COMMENTS.Q.MEASURED
     ." Mean flow:"        CR 3 SPACES Q.MEAN . CR
     ." Flow fluct.:"      CR 3 SPACES DELTA.Q . CR
     Q.MEAN 0 =
     IF
         ." Flow ratio:"       CR 3 SPACES 0 . CR
     ELSE
         ." Flow ratio:"       CR 3 SPACES DELTA.Q Q.MEAN / . CR
     THEN
;

: SHOW.COMMENTS.P.MEASURED
     ." Mean pressure:"    CR 3 SPACES P.MEAN . CR
     ." Pressure fluct.:"  CR 3 SPACES DELTA.P . CR
     P.MEAN 0 =
     IF
         ." Pressure ratio:"  CR 3 SPACES 0 .
     ELSE
         ." Pressure ratio:"  CR 3 SPACES DELTA.P P.MEAN / .
     THEN
     -1. 3. FIX.FORMAT                      \ Write numbers in fixed point notation
;                                           \ from now on

: BOTTOM.LINE.DUMP
     {BOTLINE} SCREEN.CLEAR
     ." Do you want to have this graphic on the printer? (Y/N)"
     CURSOR.OFF
     PCKEY ?DROP 89 =
     IF
         {BOTLINE} SCREEN.CLEAR
         ." Is your printer ready? (Y/N)"
         CURSOR.OFF
         PCKEY ?DROP 89 =
         IF
             {BOTLINE} SCREEN.CLEAR
             SCREEN.PRINT
         THEN
     THEN
     BOTTOM.LINE.PLOT&PRINT
;
```

```
Plot one signal in the full-screen vuport
PLOT.1.SIGNAL
   -1. 3. FIX.FORMAT
   GRAPHICS.DISPLAY
   BEGIN.PLOT.SIGNAL
   VU.1
   END.PLOT.SIGNAL
   CURSOR.OFF
   SHOW.COMMENTS.GENERAL
   SHOW.COMMENTS.Q.MEASURED
   SHOW.COMMENTS.P.MEASURED
   BOTTOM.LINE.DUMP


\ Plot 4 signals in 4 small vuports
PLOT.4.SIGNALS
   -1. 3. FIX.FORMAT
   GRAPHICS.DISPLAY
   BEGIN.PLOT.SIGNAL
   VU.4.1
   END.PLOT.SIGNAL
   BEGIN.PLOT.SIGNAL
   VU.4.2
   END.PLOT.SIGNAL
   BEGIN.PLOT.SIGNAL
   VU.4.3
   END.PLOT.SIGNAL
   BEGIN.PLOT.SIGNAL
   VU.4.4
   END.PLOT.SIGNAL
   CURSOR.OFF
   SHOW.COMMENTS.GENERAL
   SHOW.COMMENTS.Q.MEASURED
   SHOW.COMMENTS.P.MEASURED
   BOTTOM.LINE.DUMP


\ Lay-out of information of the data-array PUMPCHAR and the string-arrays
\ SUPERSCRIPT, SUBSCRIPT, PUMPINFO.1 and PUMPINFO.2
\ The numbers are presented in scientific notation
PRINT.DATA
   PUMPDATA.IN
   9. 2. SCI.FORMAT
   16 SPACES
   4  1 DO
        SUPERSCRIPT "[ I ] "TYPE 3 SPACES
   LOOP
   19 SPACES SUPERSCRIPT "[ 4 ] "TYPE CR CR
   13  1 DO
        PUMPINFO.1 "[ I ] "TYPE 3 SPACES
        PUMPCHAR [ I , 1 ] . 3 SPACES
        PUMPCHAR [ I , 2 ] . 3 SPACES
        PUMPCHAR [ I , 3 ] . 3 SPACES
        PUMPINFO.2 "[ I ] "TYPE 3 SPACES
```

```
        PUMPCHAR [ I , 4 ] . CR
   LOOP  CR CR
   16 SPACES
   5  1 DO
        SUBSCRIPT "[ I ] "TYPE 3 SPACES
   LOOP CR CR
   16 SPACES
   PUMPCHAR [ 13 , 1 ] . 3 SPACES
   PUMPCHAR [ 13 , 2 ] . 3 SPACES
   PUMPCHAR [ 13 , 3 ] . 3 SPACES
   PUMPCHAR [ 13 , 4 ] . 3 SPACES CR CR CR
;

\ Print the information written in PRINT.DATA on your screen
: PRINT.TO.SCREEN
    {TOT-TOP} SCREEN.CLEAR CR CR
    ." Type Y if you want to have your data on the screen." CR
    ." Any other key takes you back to the PLOT&PRINT MENU."
    PCKEY ?DROP 89 =
    IF
         {TOT-TOP} SCREEN.CLEAR CR CR
         PRINT.DATA
         ." Press any key to continue."
         PCKEY ?DROP DROP
         ALL.S ARRAY.EDIT
         -1. 3. FIX.FORMAT
         BOTTOM.LINE.PLOT&PRINT
    ELSE
         PLOT&PRINT.MENU
    THEN
;

\ Print the information written in PRINT.DATA on a printer
: PRINT.TO.PRINTER
    {TOT-TOP} SCREEN.CLEAR CR CR
    ." Type Y if you want to have your data on the printer." CR
    ." Any other key takes you back to the PLOT&PRINT MENU."
    PCKEY ?DROP 89 =
    IF
         {BOTLINE} SCREEN.CLEAR
         ." Is you printer ready? (Y/N)"
         CURSOR.OFF
         PCKEY ?DROP 89 =
         IF
              {TOT-TOP} SCREEN.CLEAR CR CR
              OUT>PRINTER                       \ Send information to printer
              PRINT.DATA
              CONSOLE                           \ Print information on screen too
              -1. 3. FIX.FORMAT
              BOTTOM.LINE.PLOT&PRINT
         THEN
    ELSE
         PLOT&PRINT.MENU
    THEN
```

```
Give the function keys the following functions
PLOT&PRINT.KEYS
   F1  FUNCTION.KEY.DOES PLOT.1.SIGNAL
   F2  FUNCTION.KEY.DOES PLOT.4.SIGNALS
   F3  FUNCTION.KEY.DOES NOP
   F4  FUNCTION.KEY.DOES PLOT.Q.THEORY
   F5  FUNCTION.KEY.DOES PLOT.P.THEORY
   F6  FUNCTION.KEY.DOES GOBACK.MAIN       \ MAIN.PROGRAM is not known to the
   F7  FUNCTION.KEY.DOES PRINT.TO.SCREEN   \ system before loading this pro-
   F8  FUNCTION.KEY.DOES PRINT.TO.PRINTER  \ gram the first time. A execution
   F9  FUNCTION.KEY.DOES LEAVE.PROGRAM     \ variable is therefore used.
   F10 FUNCTION.KEY.DOES LEAVE.ASYST


Start the Plot&Print Program
PLOT&PRINT.PROGRAM
   STORE.FUNCTION.KEYS                     \ Store function keys which were
   PLOT&PRINT.KEYS                         \ used before the start of PLOT&
   PLOT&PRINT.MENU                         \ PRINT.PROGRAM
   INTERPRET.KEYS                          \ Wait for a key to be hit
NESCAPE:
   RESTORE.FUNCTION.KEYS MAIN.MENU


Give the function keys the following functions
MAIN.KEYS
   F1  FUNCTION.KEY.DOES MEASURE
   F2  FUNCTION.KEY.DOES DIRECTORY
   F3  FUNCTION.KEY.DOES OUTPUT.DATA.FILE
   F4  FUNCTION.KEY.DOES INPUT.DATA.FILE
   F5  FUNCTION.KEY.DOES CHANGE.OPTIONS
   F6  FUNCTION.KEY.DOES PLOT&PRINT.PROGRAM
   F7  FUNCTION.KEY.DOES PLOT&PRINT.PROGRAM
   F8  FUNCTION.KEY.DOES SMOOTH.SIGNALS
   F9  FUNCTION.KEY.DOES LEAVE.PROGRAM
   F10 FUNCTION.KEY.DOES LEAVE.ASYST


Start the Main Program
MAIN.PROGRAM
   STORE.FUNCTION.KEYS
   MAIN.KEYS
   MAIN.MENU
   INTERPRET.KEYS
NESCAPE:
   RESTORE.FUNCTION.KEYS MAIN.MENU


NSTALL MAIN.PROGRAM IN GOBACK.MAIN         \ Install procedure MAIN.PROGRAM
                                           \ in the execution variable
                                           \ GOBACK.MAIN (see PLOT&PRINT.KEYS)
```

```
\ Clear the functions of all keys
: CLEAR.FKEYS
    133 0 DO
         I FUNCTION.KEY.DOES NOP
    LOOP
;

\ Start the program
: RUN
     CLEAR.FKEYS
     MAIN.PROGRAM
ONERR:
     {TOT-TOP} SCREEN.CLEAR CR CR
     ." Unrecoverable error. Type <ctrl-Break> to restart."
     PCKEY ?DROP DROP
     MAIN.PROGRAM
 ;
```

```
EAL DIM[ 2 , 12 ] ARRAY COMP.INPUT
IM[ 1000 , 7 ] ARRAY SIN&COS
IM[ 1 ] ARRAY DUMARRAY

IN&COS XSECT[ ! , 7 ] []RAMP
IN&COS XSECT[ ! , 7 ] .360 * SIN&COS XSECT[ ! , 7 ] :=

 START.COMP
    OMEGA COMP.INPUT [ 1 , 1 ] :=
    OMEGA 2 * COMP.INPUT [ 2 , 1 ] :=


 COMP.CALCULATE
    DEG
    COMP.INPUT
    OMEGA 2 / PI / STROKE.VOL * COMP.INPUT [ 1 , 2 ] :=
    OMEGA 2 / PI / STROKE.VOL * COMP.INPUT [ 2 , 2 ] :=
    2 COL TABLE 2 ** D.R * 9810 D.HEAD * + P.ATM + 3 COL TABLE :=
    AIR.SUPPLY 0 =
    IF
         P.ATM D.AIRCH.VOL * GAS.CONST / 3 COL TABLE 2 ** / 4 COL TABLE :=
    ELSE
         D.AIRCH.VOL GAS.CONST / 3 COL TABLE / 4 COL TABLE :=
    THEN
    2 COL TABLE 2 ** D.R * 3 COL TABLE / 5 COL TABLE :=
    1 COL TABLE D.L * 2 COL TABLE * 3 COL TABLE / 6 COL TABLE :=
    1 1 COL TABLE 2 ** D.L * 4 COL TABLE * - 7 COL TABLE :=
    1 COL TABLE D.R * 4 COL TABLE * 2 COL TABLE * 8 COL TABLE :=
    7 COL TABLE 2 ** 8 COL TABLE 2 * 2 ** + -.5 ** 9 COL TABLE :=
    5 COL TABLE 2 ** 6 COL TABLE 2 ** +
    7 COL TABLE 2 ** 8 COL TABLE 2 ** + / .5 ** 10 COL TABLE :=
    8 COL TABLE 7 COL TABLE / ATAN 11 COL TABLE :=
    6 COL TABLE 5 COL TABLE / ATAN 12 COL TABLE :=
    3 1 DO
         COMP.INPUT [ I , 11 ]  0 <
         IF
              COMP.INPUT [ I , 11 ] 180 + COMP.INPUT [ I , 11 ] :=
         THEN
         COMP.INPUT [ I , 12 ]  0 <
         IF
              COMP.INPUT [ I , 12 ] 180 + COMP.INPUT [ I , 12 ] :=
         THEN
    LOOP
    11 COL TABLE 12 COL TABLE + -3. / 12 COL TABLE :=
    8 COL TABLE 2 * 7 COL TABLE / ATAN NEG 11 COL TABLE :=
    3 1 DO
         COMP.INPUT [ I , 11 ]  0 >
         IF
              COMP.INPUT [ I , 11 ] 180 - COMP.INPUT [ I , 11 ] :=
         THEN
    LOOP


 SIN&COS.CALCULATE
```

```
    SIN&COS XSECT[ ! , 7 ] COMP.INPUT [ 1 , 11 ] + SIN
    COMP.INPUT [ 1 , 9 ] * PI * 2 / SIN&COS XSECT[ ! , 1 ] :=
    SIN&COS XSECT[ ! , 7 ] 2 * COMP.INPUT [ 2 , 11 ] + COS
    COMP.INPUT [ 2 , 9 ] * -2 * 3 / SIN&COS XSECT[ ! , 2 ] :=
    SIN&COS XSECT[ ! , 7 ] COMP.INPUT [ 1 , 12 ] + SIN
    COMP.INPUT [ 1 , 10 ] * PI * 2 / SIN&COS XSECT[ ! , 3 ] :=
    SIN&COS XSECT[ ! , 7 ] 2 * COMP.INPUT [ 2 , 12 ] + COS
    COMP.INPUT [ 2 , 10 ] * -2 * 3 / SIN&COS XSECT[ ! , 4 ] :=
    SIN&COS XSECT[ ! , 1 ] SIN&COS XSECT[ ! , 2 ] + SIN&COS XSECT[ ! , 5 ] :=
    SIN&COS XSECT[ ! , 3 ] SIN&COS XSECT[ ! , 4 ] + SIN&COS XSECT[ ! , 6 ] :=
;

: END.SIN&COS
    DUMARRAY ARRAY.EDIT
    PUMPDATA.IN
    COMP.INPUT ARRAY.EDIT
    START.COMP
    COMP.CALCULATE
    DUMARRAY ARRAY.EDIT
    SIN&COS.CALCULATE
;

: SHOW.COMMENTS.Q.THEORY
    ." Mean flow:" CR 3 SPACES COMP.INPUT [ 1 , 2 ] 1E+03 * . CR
    ." Flow fluct.:" CR 3 SPACES SIN&COS XSECT[ ! , 5 ] []MAX
                     COMP.INPUT [ 1 , 2 ] 1E+03 * * . CR
    ." Flow ratio:" CR 3 SPACES SIN&COS XSECT[ ! , 5 ] []MAX . CR CR
;

: SHOW.COMMENTS.P.THEORY
    ." Mean Pressure:" CR 3 SPACES COMP.INPUT [ 1 , 3 ] 1E+05 / . CR
    ." Pressure fluct.:" CR 3 SPACES SIN&COS XSECT[ ! , 6 ] []MAX
                         COMP.INPUT [ 1 , 3 ] 1E+05 / * . CR
    ." Pressure ratio:" CR 3 SPACES SIN&COS XSECT[ ! , 6 ] []MAX . CR CR
;

: SHOW.FLOW
    {COMM} SCREEN.CLEAR
    9. 2. SCI.FORMAT
    ." THEORY" CR CR
    SHOW.COMMENTS.Q.THEORY CR CR
    ." MEASURED" CR CR
    SHOW.COMMENTS.Q.MEASURED
    -1. 3. FIX.FORMAT
;

: SHOW.PRESSURE
    {COMM} SCREEN.CLEAR
    9. 2. SCI.FORMAT
    ." THEORY" CR CR
    SHOW.COMMENTS.P.THEORY CR CR
    ." MEASURED" CR CR
    SHOW.COMMENTS.P.MEASURED
;
```

```
FLOW.SCALE
   WORLD.COORDS
   0    360.  HORIZONTAL WORLD.SET
   -1. 4. FIX.FORMAT
   SIN&COS XSECT[ ! , 5 ]  []MIN/MAX  VERTICAL   WORLD.SET
   NORMAL.COORDS
   .25   .15  AXIS.POINT
   XY.AXIS.PLOT
   OUTLINE


PRESSURE.SCALE
   WORLD.COORDS
   0    360.  HORIZONTAL WORLD.SET
   -1. 4. FIX.FORMAT
   SIN&COS XSECT[ ! , 6 ]  []MIN/MAX  VERTICAL   WORLD.SET
   NORMAL.COORDS
   .25   .15  AXIS.POINT
   XY.AXIS.PLOT
   OUTLINE


Q.COMP
   SIN&COS XSECT[ ! , 7 ]  SIN&COS XSECT[ ! , 5 ]  XY.DATA.PLOT


P.COMP
   SIN&COS XSECT[ ! , 7 ]  SIN&COS XSECT[ ! , 6 ]  XY.DATA.PLOT


Q.COMP.LABEL
   GRAPHICS.READOUT
   NORMAL.COORDS
   .35   .95  POSITION
   " OUTPUT FUNCTION FLOW" LABEL
   .55   .05  POSITION
   " PISTON POSITION" LABEL
   .10   .70  POSITION
   270 LABEL.DIR
   " FLOW RATIO" LABEL


P.COMP.LABEL
   GRAPHICS.READOUT
   NORMAL.COORDS
   .35   .95  POSITION
   " OUTPUT FUNCTION PRESSURE" LABEL
   .55   .05  POSITION
   " PISTON POSITION" LABEL
   .10   .70  POSITION
   270 LABEL.DIR
   " PRESSURE RATIO" LABEL
```

```
: PLOT.Q.COMP
     GRAPHICS.DISPLAY
     VU.1
     SIGNAL.VU
     .25   .15  AXIS.POINT
     FLOW.SCALE
     Q.COMP
     Q.COMP.LABEL
     CURSOR.OFF
;

: PLOT.P.COMP
     GRAPHICS.DISPLAY
     VU.1
     SIGNAL.VU
     PRESSURE.SCALE
     P.COMP
     P.COMP.LABEL
     CURSOR.OFF
;

: PLOT.FLOW
     END.SIN&COS
     PLOT.Q.COMP
     SHOW.FLOW
     BOTTOM.LINE.DUMP
;

: PLOT.PRESSURE
     END.SIN&COS
     PLOT.P.COMP
     SHOW.PRESSURE
     BOTTOM.LINE.DUMP
;

INSTALL PLOT.FLOW IN PLOT.Q.THEORY
INSTALL PLOT.PRESSURE IN PLOT.P.THEORY
```

## APPENDIX 5C A BRIEF USER'S GUIDE OF MEASURE.DMO

Turn on the computer and put the DOS 2.1 disk in drive A.
After a while date and time are given and after that an "A" prompt.
Replace the DOS 2.1 disk with the MEASURE disk and put the Master disk of ASYST in drive B.
Type MEASURE. The computer then loads ASYST together with the compiled version of MEASURE.DMO into its memory.
The following message appears on the screen: " Type any key to continue." Answering this, the computer returns with an "OK" prompt.
Replace the ASYST Master disk with a DATA disk and type RUN. The program is started and the Main Menu appears on screen. It might happen that the function keys are "dead". In this case one has to type <ctrl-Break> and again RUN.
You are now ready to operate with the measuring program.

Before starting to measure the first time you have to go to CHANGE OPTIONS because the computer has to know at which sample time it has to sample the signals and how many samples it has to take for each signal.
Now you can start MEASURE. The Main Menu will disappear and after the measuring will appear on the screen again.
Before saving the measured data, you have to go to the PLOT&PRINT PROGRAM and plot all four signals on the screen. This is necessary to get all the information of the measurement in the array together with the pump data. This doesn't seem very logical but it has two advantages. At first you can see if it is a good measurement or not (if not, you don't have to save the data) and secondly it made the writing of the program easier.
After saving the data the following measurement can be obtained.

With READ DATA it is possible to print the plots at any time you want. The printing of a graph takes about seven minutes which is a terribly long time if you want to continue measuring.

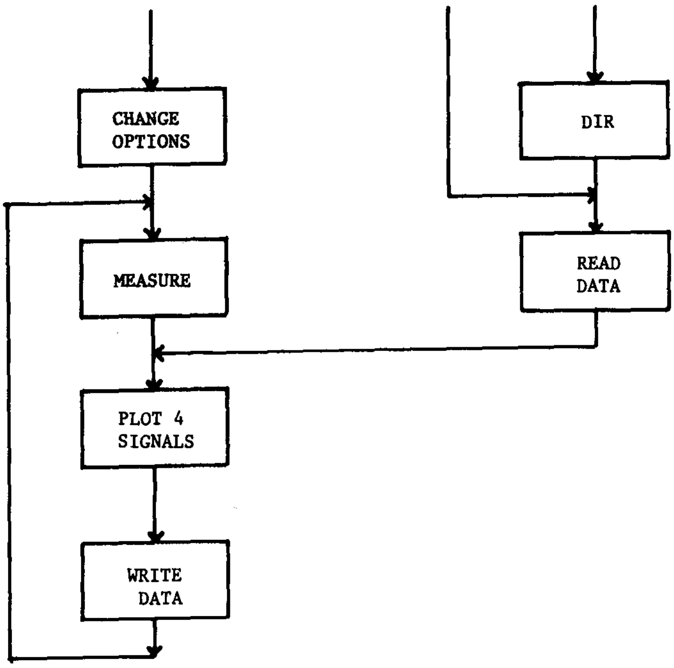


Figure 5.2 Block diagram of how to operate with the program.

In figure 5.2 a block diagram is drawn of the information of this Appendix. The program has many more possibilities which will become clear after a short time in working with the program.

## APPENDIX 6A THE DEFINITION OF THE GAS CONSTANT

During most of the measurements the mimimum and the maximum of the air volume fluctuations in the delivery airchamber were measured. These measurements are not very accurate because the waterlevel was changing rapidly.
The results of these measurements are shown in table 6A.1.

With use of the theory of par. 3.5 we are able to write

$$\left(\frac{p_{max}}{p_{min}}\right) = \left(\frac{h_{a,max} \cdot A_a}{h_{a,min} \cdot A_a}\right)^k \tag{6A.1}$$

in which $h_a$ is the height of the air column in the delivery airchamber and

$A_a$ is the cross-section area of the airchamber.

Table 6A.1 Performed measurements to define the value of the gas constant. The value of k in column 8 has been calculated with use of eq. (6A.1).

| nr. | $p_{max}$ (bar) | $p_{min}$ (bar) | $h_{max}$ (m) | $h_{min}$ (m) | $\frac{p_{max}}{p_{min}}$ | $\frac{h_{max}}{h_{min}}$ | k | Δk |
|---|---|---|---|---|---|---|---|---|
| 5 | 1.93 | 1.65 | 0.295 | 0.265 | 1.170 | 1.113 | 1.46 | -0.01 |
| 6 | 2.40 | 1.92 | 0.250 | 0.220 | 1.250 | 1.136 | 1.74 | -0.29 |
| 7 | 2.34 | 1.90 | 0.252 | 0.220 | 1.232 | 1.145 | 1.54 | -0.09 |
| 8 | 2.52 | 2.02 | 0.236 | 0.204 | 1.248 | 1.157 | 1.52 | -0.07 |
| 9 | 2.67 | 2.11 | 0.225 | 0.190 | 1.265 | 1.184 | 1.39 | 0.06 |
| 13 | 1.81 | 1.39 | 0.173 | 0.143 | 1.302 | 1.210 | 1.39 | 0.06 |
| 14 | 2.07 | 1.51 | 0.155 | 0.125 | 1.371 | 1.240 | 1.47 | -0.02 |
| 15 | 2.35 | 1.65 | 0.142 | 0.112 | 1.424 | 1.268 | 1.49 | -0.04 |
| 16 | 2.48 | 1.72 | 0.137 | 0.107 | 1.442 | 1.280 | 1.48 | -0.03 |
| 17 | 2.74 | 1.85 | 0.130 | 0.095 | 1.481 | 1.368 | 1.25 | 0.20 |
| 18 | 2.98 | 1.94 | 0.120 | 0.090 | 1.536 | 1.333 | 1.49 | -0.04 |
| 22 | 2.04 | 1.26 | 0.093 | 0.068 | 1.619 | 1.368 | 1.54 | -0.09 |
| 23 | 2.32 | 1.36 | 0.085 | 0.060 | 1.706 | 1.417 | 1.53 | -0.08 |
| 24 | 2.67 | 1.49 | 0.076 | 0.050 | 1.792 | 1.520 | 1.40 | 0.05 |
| 25 | 2.90 | 1.50 | 0.070 | 0.045 | 1.933 | 1.556 | 1.49 | -0.04 |
| 26 | 3.04 | 1.58 | 0.068 | 0.040 | 1.924 | 1.700 | 1.23 | 0.22 |
| 27 | 3.26 | 1.64 | 0.066 | 0.035 | 1.988 | 1.886 | 1.08 | 0.37 |
| 31 | 1.80 | 1.38 | 0.190 | 0.158 | 1.304 | 1.203 | 1.44 | 0.01 |
| 32 | 2.05 | 1.57 | 0.190 | 0.158 | 1.306 | 1.203 | 1.45 | -0.00 |
| 33 | 2.33 | 1.73 | 0.190 | 0.158 | 1.347 | 1.203 | 1.61 | -0.16 |
| 34 | 2.54 | 1.78 | 0.142 | 0.110 | 1.427 | 1.291 | 1.39 | 0.06 |
| 35 | 2.77 | 1.91 | 0.142 | 0.110 | 1.450 | 1.291 | 1.46 | -0.01 |

The mean value of k is 1.447 . Together with the results of table 6A.1 the standard deviation $\sigma^2$ now becomes

$$\sigma^2 = \frac{1}{N} \cdot \sum_{i=1}^{N} (\bar{k} - \Delta k_i)^2 = 0.017$$

The mean standard deviation $\bar{\sigma}$ thus becomes

$$\bar{\sigma} = \frac{\sqrt{\sigma^2}}{\sqrt{N}} = 0.028$$

With these calculations k appears to be 1.45 ± 0.03. For air the gas constant can never be higher than 1.4. Considering the accuracy of the measurements we may assume adiabatic compression and expansion of the air in the airchamber during one cycle. Hence $k=\gamma=1.4$ .

## APPENDIX 6B NUMERICAL RESULTS OF THE EXPERIMENTS

Experiments 1 to 27 concern measurements with a constant air mass. Experiments 28 to 30 concern measurements near resonance speeds. Experiments 31 to 35 concern measurements in which air is supplied to the delivery airchamber.

Table 6B.1 The performed experiments. In the first and second columns the experiment number and the file name in which the results are stored, are given. In the third column one finds the adjusted $\nabla_s/\nabla_{atm}$, in column four the adjusted delivery head (in m) and in the fifth column the measured rotational speed (in rad/s). In columns 6, 7 and 8 the calculated mean flow (in $m^3$), mean pressure (in bar) and resonance rotational speed (in rad/s) are given.

| nr. | filename | $\frac{\nabla_s}{\nabla_{atm}}$ | $H_d$ (m) | $\omega$ (rad/s) | $\bar{q}_c$ ($m^3/s$) | $\bar{p}_1$ (bar) | $\omega_e$ (rad/s) |
|---|---|---|---|---|---|---|---|
| 1 | s0917.dat | 1.65E-01 | 1.00E+00 | 3.47E+00 | 4.20E-04 | 1.16E+00 | 6.40E-01 |
| 2 | s0917.dat | 1.65E-01 | 1.00E+00 | 5.93E+00 | 7.17E-04 | 1.33E+00 | 7.20E-01 |
| 3 | s0917.dat | 1.65E-01 | 1.00E+00 | 8.45E+00 | 1.02E-03 | 1.56E+00 | 8.44E-01 |
| 4 | s0916.dat | 1.65E-01 | 5.00E+00 | 3.79E+00 | 4.58E-04 | 1.59E+00 | 8.60E-01 |
| 5 | s0916.dat | 1.65E-01 | 5.00E+00 | 6.55E+00 | 7.92E-04 | 1.77E+00 | 9.58E-01 |
| 6 | s0916.dat | 1.65E-01 | 5.00E+00 | 1.01E+01 | 1.22E-03 | 2.14E+00 | 1.16E+00 |
| 7 | s0916.dat | 1.65E-01 | 1.00E+01 | 4.65E+00 | 5.62E-04 | 2.13E+00 | 1.15E+00 |
| 8 | s0916.dat | 1.65E-01 | 1.00E+01 | 6.49E+00 | 7.85E-04 | 2.26E+00 | 1.22E+00 |
| 9 | s0916.dat | 1.65E-01 | 1.00E+01 | 8.01E+00 | 9.69E-04 | 2.40E+00 | 1.30E+00 |
| 10 | s0917.dat | 3.30E-01 | 1.00E+00 | 3.48E+00 | 4.21E-04 | 1.18E+00 | 9.06E-01 |
| 11 | s0917.dat | 3.30E-01 | 1.00E+00 | 5.97E+00 | 7.22E-04 | 1.33E+00 | 1.02E+00 |
| 12 | s0917.dat | 3.30E-01 | 1.00E+00 | 8.49E+00 | 1.03E-03 | 1.57E+00 | 1.20E+00 |
| 13 | s0916.dat | 3.30E-01 | 5.00E+00 | 3.81E+00 | 4.61E-04 | 1.59E+00 | 1.22E+00 |
| 14 | s0916.dat | 3.30E-01 | 5.00E+00 | 6.49E+00 | 7.85E-04 | 1.77E+00 | 1.35E+00 |
| 15 | s0916.dat | 3.30E-01 | 5.00E+00 | 8.31E+00 | 1.01E-03 | 1.94E+00 | 1.48E+00 |
| 16 | s0916.dat | 3.30E-01 | 1.00E+01 | 3.43E+00 | 4.15E-04 | 2.07E+00 | 1.58E+00 |
| 17 | s0916.dat | 3.30E-01 | 1.00E+01 | 6.28E+00 | 7.60E-04 | 2.24E+00 | 1.71E+00 |
| 18 | s0916.dat | 3.30E-01 | 1.00E+01 | 8.10E+00 | 9.80E-04 | 2.41E+00 | 1.84E+00 |
| 19 | s0917.dat | 6.61E-01 | 1.00E+00 | 3.50E+00 | 4.23E-04 | 1.19E+00 | 1.28E+00 |
| 20 | s0917.dat | 6.61E-01 | 1.00E+00 | 5.93E+00 | 7.17E-04 | 1.33E+00 | 1.44E+00 |
| 21 | s0917.dat | 6.61E-01 | 1.00E+00 | 8.40E+00 | 1.02E-03 | 1.56E+00 | 1.68E+00 |
| 22 | s0916.dat | 6.61E-01 | 5.00E+00 | 3.51E+00 | 4.25E-04 | 1.58E+00 | 1.71E+00 |
| 23 | s0916.dat | 6.61E-01 | 5.00E+00 | 6.41E+00 | 7.75E-04 | 1.76E+00 | 1.91E+00 |
| 24 | s0916.dat | 6.61E-01 | 5.00E+00 | 8.36E+00 | 1.01E-03 | 1.94E+00 | 2.10E+00 |
| 25 | s0916.dat | 6.61E-01 | 1.00E+01 | 3.34E+00 | 4.04E-04 | 2.06E+00 | 2.23E+00 |
| 26 | s0916.dat | 6.61E-01 | 1.00E+01 | 5.20E+00 | 6.29E-04 | 2.16E+00 | 2.34E+00 |
| 27 | s0916.dat | 6.61E-01 | 1.00E+01 | 6.92E+00 | 8.37E-04 | 2.30E+00 | 2.48E+00 |
| 28 | s0919.dat | 6.61E-01 | 1.00E+01 | 1.58E+00 | 1.91E-04 | 2.01E+00 | 2.17E+00 |
| 29 | s0919.dat | 6.61E-01 | 1.00E+01 | 2.33E+00 | 2.82E-04 | 2.03E+00 | 2.19E+00 |
| 30 | s0919.dat | 6.61E-01 | 1.00E+01 | 3.09E+00 | 3.74E-04 | 2.05E+00 | 2.22E+00 |
| 31 | s0916.dat | 3.30E-01 | 5.00E+00 | 3.58E+00 | 4.33E-04 | 1.58E+00 | 9.66E-01 |
| 32 | s0916.dat | 3.30E-01 | 5.00E+00 | 6.52E+00 | 7.89E-04 | 1.77E+00 | 1.02E+00 |
| 33 | s0916.dat | 3.30E-01 | 5.00E+00 | 9.35E+00 | 1.13E-03 | 2.06E+00 | 1.10E+00 |
| 34 | s0916.dat | 3.30E-01 | 1.00E+01 | 4.57E+00 | 5.53E-04 | 2.12E+00 | 1.12E+00 |
| 35 | s0916.dat | 3.30E-01 | 1.00E+01 | 6.98E+00 | 8.44E-04 | 2.30E+00 | 1.17E+00 |

Experiments 1 to 27 concern measurements with a constant air mass. Experiments 28 to 30 concern measurements near resonance speeds. Experiments 31 to 35 concern measurements in which air is supplied to the delivery airchamber.

Table 6B.2 The measured and the theoretical values of the pressure in the delivery airchamber. In the sixth and seventh column the measured and calculated (model) mean pressure are given. In column eight and nine one finds the maxima of the measured and calculated (model) dimensionless pressure fluctuations. In the tenth column the ratio between the maxima of the theoretical and the measured dimensionless pressure fluctuations is given. In the eleventh column the ratio between the theoretical and the measured mean flow, the volumetric efficiency $\eta_{vol}$, is given.

| nr. | $\frac{\nabla_s}{\nabla_{atm}}$ | $H_d$ (m) | $\omega$ (rad/s) | $\omega_e$ (rad/s) | $\bar{p}_1$ (bar) measured | $\bar{p}_1$ (bar) theory | $\Delta\hat{p}_{1,max}$ measured | $\Delta\hat{p}_{1,max}$ theory | $\frac{\Delta\hat{p}_{1,ms}}{\Delta\hat{p}_{1,th}}$ | $\eta_{vol}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.65E-01 | 1.00E+00 | 3.47E+00 | 6.40E-01 | 1.20E+00 | 1.18E+00 | 6.34E-02 | 7.38E-02 | 8.59E-01 | 8.20E-01 |
| 2 | 1.65E-01 | 1.00E+00 | 5.93E+00 | 7.20E-01 | 1.34E+00 | 1.33E+00 | 7.37E-02 | 8.24E-02 | 8.94E-01 | 8.60E-01 |
| 3 | 1.65E-01 | 1.00E+00 | 8.45E+00 | 8.44E-01 | 1.61E+00 | 1.56E+00 | 8.49E-02 | 9.91E-02 | 8.57E-01 | 8.91E-01 |
| 4 | 1.65E-01 | 5.00E+00 | 3.79E+00 | 8.60E-01 | 1.59E+00 | 1.59E+00 | 7.00E-02 | 9.78E-02 | 7.16E-01 | 8.20E-01 |
| 5 | 1.65E-01 | 5.00E+00 | 6.55E+00 | 9.58E-01 | 1.78E+00 | 1.77E+00 | 8.44E-02 | 1.10E-01 | 7.71E-01 | 8.18E-01 |
| 6 | 1.65E-01 | 5.00E+00 | 1.01E+01 | 1.16E+00 | 2.14E+00 | 2.14E+00 | 1.22E-01 | 1.32E-01 | 9.27E-01 | 8.46E-01 |
| 7 | 1.65E-01 | 1.00E+01 | 4.65E+00 | 1.15E+00 | 2.11E+00 | 2.13E+00 | 1.08E-01 | 1.30E-01 | 8.32E-01 | 7.95E-01 |
| 8 | 1.65E-01 | 1.00E+01 | 6.49E+00 | 1.22E+00 | 2.25E+00 | 2.26E+00 | 1.19E-01 | 1.38E-01 | 8.60E-01 | 8.31E-01 |
| 9 | 1.65E-01 | 1.00E+01 | 8.01E+00 | 1.30E+00 | 2.38E+00 | 2.40E+00 | 1.23E-01 | 1.46E-01 | 8.40E-01 | 8.40E-01 |
| 10 | 3.30E-01 | 1.00E+00 | 3.48E+00 | 9.06E-01 | 1.20E+00 | 1.18E+00 | 1.18E-01 | 1.48E-01 | 7.99E-01 | 8.39E-01 |
| 11 | 3.30E-01 | 1.00E+00 | 5.97E+00 | 1.02E+00 | 1.37E+00 | 1.33E+00 | 1.39E-01 | 1.69E-01 | 8.25E-01 | 8.77E-01 |
| 12 | 3.30E-01 | 1.00E+00 | 8.49E+00 | 1.20E+00 | 1.58E+00 | 1.57E+00 | 1.65E-01 | 1.94E-01 | 8.49E-01 | 8.55E-01 |
| 13 | 3.30E-01 | 5.00E+00 | 3.81E+00 | 1.22E+00 | 1.58E+00 | 1.59E+00 | 1.45E-01 | 1.94E-01 | 7.46E-01 | 7.68E-01 |
| 14 | 3.30E-01 | 5.00E+00 | 6.49E+00 | 1.35E+00 | 1.77E+00 | 1.77E+00 | 1.67E-01 | 2.18E-01 | 7.67E-01 | 8.52E-01 |
| 15 | 3.30E-01 | 5.00E+00 | 8.31E+00 | 1.48E+00 | 1.96E+00 | 1.94E+00 | 1.87E-01 | 2.41E-01 | 7.75E-01 | 8.49E-01 |
| 16 | 3.30E-01 | 1.00E+01 | 3.43E+00 | 1.58E+00 | 2.06E+00 | 2.07E+00 | 2.06E-01 | 2.53E-01 | 8.13E-01 | 7.35E-01 |
| 17 | 3.30E-01 | 1.00E+01 | 6.28E+00 | 1.71E+00 | 2.24E+00 | 2.24E+00 | 2.21E-01 | 2.76E-01 | 8.02E-01 | 8.16E-01 |
| 18 | 3.30E-01 | 1.00E+01 | 8.10E+00 | 1.84E+00 | 2.40E+00 | 2.41E+00 | 2.41E-01 | 2.95E-01 | 8.16E-01 | 8.24E-01 |
| 19 | 6.61E-01 | 1.00E+00 | 3.50E+00 | 1.28E+00 | 1.21E+00 | 1.19E+00 | 1.96E-01 | 2.98E-01 | 6.57E-01 | 8.36E-01 |
| 20 | 6.61E-01 | 1.00E+00 | 5.93E+00 | 1.44E+00 | 1.37E+00 | 1.33E+00 | 2.33E-01 | 3.38E-01 | 6.90E-01 | 8.73E-01 |
| 21 | 6.61E-01 | 1.00E+00 | 8.40E+00 | 1.68E+00 | 1.61E+00 | 1.56E+00 | 2.93E-01 | 3.97E-01 | 7.38E-01 | 8.72E-01 |
| 22 | 6.61E-01 | 5.00E+00 | 3.51E+00 | 1.71E+00 | 1.59E+00 | 1.58E+00 | 2.83E-01 | 3.92E-01 | 7.22E-01 | 7.61E-01 |
| 23 | 6.61E-01 | 5.00E+00 | 6.41E+00 | 1.91E+00 | 1.76E+00 | 1.76E+00 | 3.09E-01 | 4.34E-01 | 7.12E-01 | 8.02E-01 |
| 24 | 6.61E-01 | 5.00E+00 | 8.36E+00 | 2.10E+00 | 1.98E+00 | 1.94E+00 | 3.47E-01 | 4.88E-01 | 7.11E-01 | 8.50E-01 |
| 25 | 6.61E-01 | 1.00E+01 | 3.34E+00 | 2.23E+00 | 2.06E+00 | 2.06E+00 | 4.09E-01 | 5.08E-01 | 8.06E-01 | 6.68E-01 |
| 26 | 6.61E-01 | 1.00E+01 | 5.20E+00 | 2.34E+00 | 2.17E+00 | 2.16E+00 | 3.99E-01 | 5.35E-01 | 7.46E-01 | 7.66E-01 |
| 27 | 6.61E-01 | 1.00E+01 | 6.92E+00 | 2.48E+00 | 2.29E+00 | 2.30E+00 | 4.24E-01 | 5.64E-01 | 7.51E-01 | 8.11E-01 |
| 28 | 6.61E-01 | 1.00E+01 | 1.58E+00 | 2.17E+00 | 1.97E+00 | 2.01E+00 | 4.04E-01 | 4.86E-01 | 8.32E-01 | 1.17E+00 |
| 29 | 6.61E-01 | 1.00E+01 | 2.33E+00 | 2.19E+00 | 2.02E+00 | 2.03E+00 | 5.47E-01 | 4.98E-01 | 1.10E+00 | 6.10E-01 |
| 30 | 6.61E-01 | 1.00E+01 | 3.09E+00 | 2.22E+00 | 2.06E+00 | 2.05E+00 | 4.56E-01 | 5.08E-01 | 8.98E-01 | 6.82E-01 |
| 31 | 3.30E-01 | 5.00E+00 | 3.58E+00 | 9.66E-01 | 1.57E+00 | 1.58E+00 | 1.39E-01 | 1.24E-01 | 1.12E+00 | 7.87E-01 |
| 32 | 3.30E-01 | 5.00E+00 | 6.52E+00 | 1.02E+00 | 1.79E+00 | 1.77E+00 | 1.47E-01 | 1.24E-01 | 1.18E+00 | 8.64E-01 |
| 33 | 3.30E-01 | 5.00E+00 | 9.35E+00 | 1.10E+00 | 2.01E+00 | 2.06E+00 | 1.56E-01 | 1.24E-01 | 1.26E+00 | 8.27E-01 |
| 34 | 3.30E-01 | 1.00E+01 | 4.57E+00 | 1.12E+00 | 2.13E+00 | 2.12E+00 | 1.94E-01 | 1.24E-01 | 1.56E+00 | 7.98E-01 |
| 35 | 3.30E-01 | 1.00E+01 | 6.98E+00 | 1.17E+00 | 2.30E+00 | 2.30E+00 | 2.03E-01 | 1.24E-01 | 1.63E+00 | 8.30E-01 |

Experiments 1 to 27 concern measurements with a constant air mass. Experiments 28 to 30 concern measurements near resonance speeds. Experiments 31 to 35 concern measurements in which air is supplied to the delivery airchamber.

Table 6B.3 The measured and the theoretical values of the flow in the delivery airchamber. In the sixth and seventh column the measured and calculated (model) mean flow are given. In column eight and nine one finds the maxima of the measured and calculated (model) dimensionless flow fluctuations. In the tenth column the ratio between the maxima of the theoretical and the measured dimensionless flow fluctuations is given. In the eleventh column the ratio between the theoretical and the measured mean flow, the volumetric efficiency $\eta_{vol}$, is given.

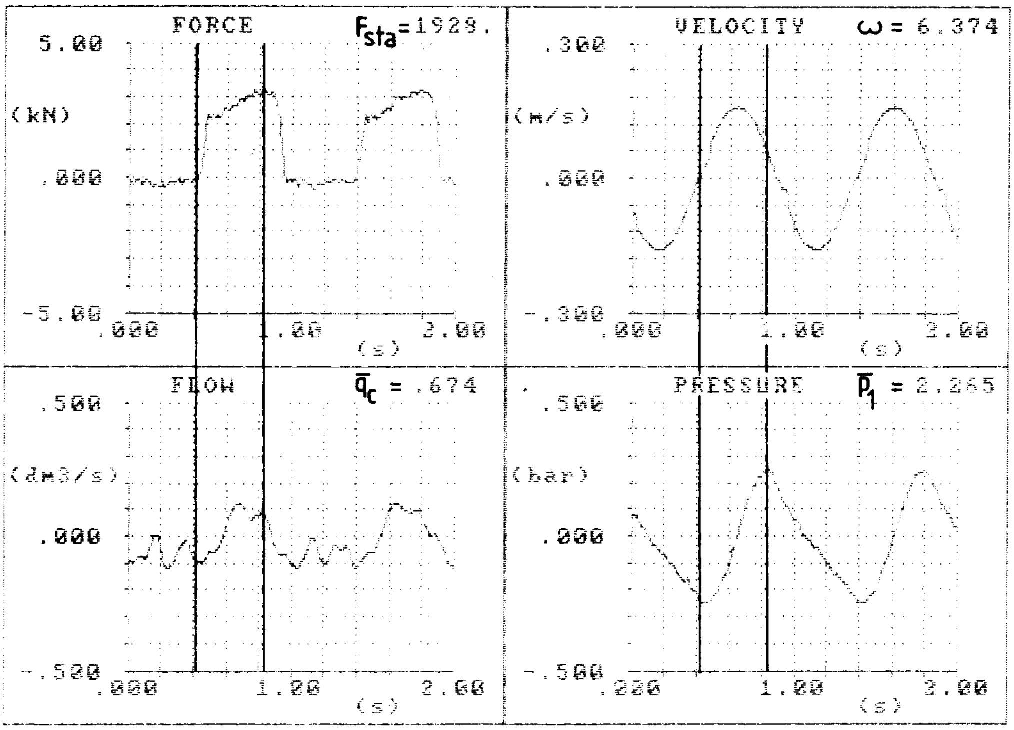
| nr. | $\frac{\nabla_s}{\nabla_{atm}}$ | $H_d$ (m) | $\omega$ (rad/s) | $\omega_e$ (rad/s) | $\bar{q}_c$ ($m^3/s$) measured | $\bar{q}_c$ ($m^3/s$) theory | $\Delta\hat{q}_{max}$ measured | $\Delta\hat{q}_{max}$ theory | $\frac{\Delta\hat{q}_{ms}}{\Delta\hat{q}_{th}}$ | $\eta_{vol}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.65E-01 | 1.00E+00 | 3.47E+00 | 6.40E-01 | 3.44E-04 | 4.20E-04 | 2.04E-01 | 5.62E-02 | 3.63E+00 | 8.20E-01 |
| 2 | 1.65E-01 | 1.00E+00 | 5.93E+00 | 7.20E-01 | 6.17E-04 | 7.17E-04 | 2.58E-01 | 2.43E-02 | 1.06E+01 | 8.60E-01 |
| 3 | 1.65E-01 | 1.00E+00 | 8.45E+00 | 8.44E-01 | 9.11E-04 | 1.02E-03 | 2.69E-01 | 1.65E-02 | 1.63E+01 | 8.91E-01 |
| 4 | 1.65E-01 | 5.00E+00 | 3.79E+00 | 8.60E-01 | 3.76E-04 | 4.58E-04 | 2.40E-01 | 8.50E-02 | 2.82E+00 | 8.20E-01 |
| 5 | 1.65E-01 | 5.00E+00 | 6.55E+00 | 9.58E-01 | 6.48E-04 | 7.92E-04 | 5.12E-02 | 3.53E-02 | 1.45E+00 | 8.18E-01 |
| 6 | 1.65E-01 | 5.00E+00 | 1.01E+01 | 1.16E+00 | 1.03E-03 | 1.22E-03 | 2.81E-01 | 2.19E-02 | 1.28E+01 | 8.46E-01 |
| 7 | 1.65E-01 | 1.00E+01 | 4.65E+00 | 1.15E+00 | 4.47E-04 | 5.62E-04 | 2.18E-01 | 1.01E-01 | 2.16E+00 | 7.95E-01 |
| 8 | 1.65E-01 | 1.00E+01 | 6.49E+00 | 1.22E+00 | 6.52E-04 | 7.85E-04 | 2.19E-01 | 5.84E-02 | 3.75E+00 | 8.31E-01 |
| 9 | 1.65E-01 | 1.00E+01 | 8.01E+00 | 1.30E+00 | 8.14E-04 | 9.69E-04 | 2.54E-01 | 4.32E-02 | 5.88E+00 | 8.40E-01 |
| 10 | 3.30E-01 | 1.00E+00 | 3.48E+00 | 9.06E-01 | 3.53E-04 | 4.21E-04 | 3.19E-01 | 1.12E-01 | 2.85E+00 | 8.39E-01 |
| 11 | 3.30E-01 | 1.00E+00 | 5.97E+00 | 1.02E+00 | 6.33E-04 | 7.22E-04 | 5.12E-01 | 4.82E-02 | 1.06E+01 | 8.77E-01 |
| 12 | 3.30E-01 | 1.00E+00 | 8.49E+00 | 1.20E+00 | 8.78E-04 | 1.03E-03 | 5.10E-01 | 3.28E-02 | 1.56E+01 | 8.55E-01 |
| 13 | 3.30E-01 | 5.00E+00 | 3.81E+00 | 1.22E+00 | 3.54E-04 | 4.61E-04 | 2.95E-01 | 1.68E-01 | 1.75E+00 | 7.68E-01 |
| 14 | 3.30E-01 | 5.00E+00 | 6.49E+00 | 1.35E+00 | 6.69E-04 | 7.85E-04 | 4.12E-01 | 7.15E-02 | 5.76E+00 | 8.52E-01 |
| 15 | 3.30E-01 | 5.00E+00 | 8.31E+00 | 1.48E+00 | 8.53E-04 | 1.01E-03 | 4.73E-01 | 5.25E-02 | 9.01E+00 | 8.49E-01 |
| 16 | 3.30E-01 | 1.00E+01 | 3.43E+00 | 1.58E+00 | 3.05E-04 | 4.15E-04 | 2.35E-01 | 3.50E-01 | 6.72E-01 | 7.35E-01 |
| 17 | 3.30E-01 | 1.00E+01 | 6.28E+00 | 1.71E+00 | 6.20E-04 | 7.60E-04 | 2.95E-01 | 1.23E-01 | 2.40E+00 | 8.16E-01 |
| 18 | 3.30E-01 | 1.00E+01 | 8.10E+00 | 1.84E+00 | 8.07E-04 | 9.80E-04 | 3.55E-01 | 8.51E-02 | 4.17E+00 | 8.24E-01 |
| 19 | 6.61E-01 | 1.00E+00 | 3.50E+00 | 1.28E+00 | 3.54E-04 | 4.23E-04 | 5.22E-01 | 2.22E-01 | 2.36E+00 | 8.36E-01 |
| 20 | 6.61E-01 | 1.00E+00 | 5.93E+00 | 1.44E+00 | 6.26E-04 | 7.17E-04 | 6.30E-01 | 9.73E-02 | 6.47E+00 | 8.73E-01 |
| 21 | 6.61E-01 | 1.00E+00 | 8.40E+00 | 1.68E+00 | 8.86E-04 | 1.02E-03 | 7.76E-01 | 6.63E-02 | 1.17E+01 | 8.72E-01 |
| 22 | 6.61E-01 | 5.00E+00 | 3.51E+00 | 1.71E+00 | 3.23E-04 | 4.25E-04 | 5.71E-01 | 3.91E-01 | 1.46E+00 | 7.61E-01 |
| 23 | 6.61E-01 | 5.00E+00 | 6.41E+00 | 1.91E+00 | 6.22E-04 | 7.75E-04 | 6.78E-01 | 1.46E-01 | 4.65E+00 | 8.02E-01 |
| 24 | 6.61E-01 | 5.00E+00 | 8.36E+00 | 2.10E+00 | 8.60E-04 | 1.01E-03 | 6.40E-01 | 1.04E-01 | 6.13E+00 | 8.50E-01 |
| 25 | 6.61E-01 | 1.00E+01 | 3.34E+00 | 2.23E+00 | 2.70E-04 | 4.04E-04 | 4.74E-01 | 7.36E-01 | 6.44E-01 | 6.68E-01 |
| 26 | 6.61E-01 | 1.00E+01 | 5.20E+00 | 2.34E+00 | 4.82E-04 | 6.29E-04 | 4.81E-01 | 3.34E-01 | 1.44E+00 | 7.66E-01 |
| 27 | 6.61E-01 | 1.00E+01 | 6.92E+00 | 2.48E+00 | 6.79E-04 | 8.37E-04 | 5.74E-01 | 2.12E-01 | 2.70E+00 | 8.11E-01 |
| 28 | 6.61E-01 | 1.00E+01 | 1.58E+00 | 2.17E+00 | 2.23E-04 | 1.91E-04 | 1.09E+00 | 3.11E+00 | 3.50E-01 | 1.17E+00 |
| 29 | 6.61E-01 | 1.00E+01 | 2.33E+00 | 2.19E+00 | 1.72E-04 | 2.82E-04 | 1.25E+00 | 1.46E+00 | 8.57E-01 | 6.10E-01 |
| 30 | 6.61E-01 | 1.00E+01 | 3.09E+00 | 2.22E+00 | 2.55E-04 | 3.74E-04 | 4.82E-01 | 8.51E-01 | 5.66E-01 | 6.82E-01 |
| 31 | 3.30E-01 | 5.00E+00 | 3.58E+00 | 9.66E-01 | 3.41E-04 | 4.33E-04 | 3.02E-01 | 1.20E-01 | 2.51E+00 | 7.87E-01 |
| 32 | 3.30E-01 | 5.00E+00 | 6.52E+00 | 1.02E+00 | 6.81E-04 | 7.89E-04 | 2.54E-01 | 4.05E-02 | 6.27E+00 | 8.64E-01 |
| 33 | 3.30E-01 | 5.00E+00 | 9.35E+00 | 1.10E+00 | 9.35E-04 | 1.13E-03 | 2.82E-01 | 2.29E-02 | 1.23E+01 | 8.27E-01 |
| 34 | 3.30E-01 | 1.00E+01 | 4.57E+00 | 1.12E+00 | 4.41E-04 | 5.53E-04 | 2.68E-01 | 9.90E-02 | 2.71E+00 | 7.98E-01 |
| 35 | 3.30E-01 | 1.00E+01 | 6.98E+00 | 1.17E+00 | 7.01E-04 | 8.44E-04 | 2.22E-01 | 4.60E-02 | 4.83E+00 | 8.30E-01 |

## APPENDIX 6C GRAPHICAL RESULTS OF SOME OF THE EXPERIMENTS

In this appendix the results of the experiments 8, 9, 17, 26 and 27 are presented as graphs.
On every first page the measured signals of the pump rod force (in kN), the velocity of the pump rod (in m/s), the flow fluctuation in the delivery line (in $dm^3/s$) and the pressure fluctuation in the delivery airchamber (in bar) are shown as functions of the time (in s). The values in the right upper corner of each graph correspond with the static pump rod force (in N), due to the static head, the rotational speed of the pump rod (in rad/s), the mean flow through the delivery line (in $dm^3/s$) and the mean pressure in the delivery airchamber (in bar) respectively.

In all graphs two vertical lines have been drawn. The left lines correspond with the moment at which the piston is at the bottom dead center (BDC). The right lines correspond with the moment at which the pressure in the delivery airchamber reaches its highest value. As one can see, the pump rod force reaches its highest value at this same moment. With a little recalculation one can see that this moment is about 2.8 rad delayed compared with the moment the piston is at the BDC.

On every second page other pump data corresponding with the experiments is given as well as the theoretical values of the dimensionless pressure fluctuations in the delivery airchamber as a function of the piston position. It gives an impression of the similarity between experiments and model. Further elaboration must prove this similarity.



**Date: 09/22/86**
**Exp. number: 8**
**No air supply.**
**Delivery head:**
**1.00E 1**

**Time one sample:**
**4.00E 0**
**Number of samp.:**
**500**

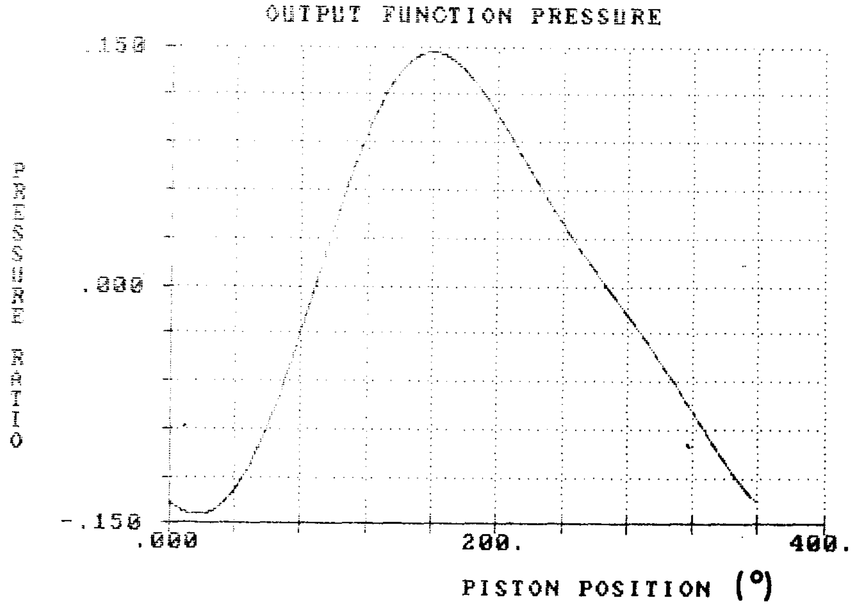
**Mean flow:**
6.74E -1
**Flow fluct.:**
1.22E -1
**Flow ratio:**
1.81E -1
**Mean pressure:**
2.27E 0
**Pressure fluct.:**
2.49E -1
**Pressure ratio:**
1.10E -1

THEORY

Mean Pressure:
2.26E 0
Pressure fluct.:
3.31E -1
Pressure ratio:
1.49E -1

MEASURED

Mean pressure:
2.27E 0
Pressure fluct.:
2.49E -1
Pressure ratio:
1.10E -1

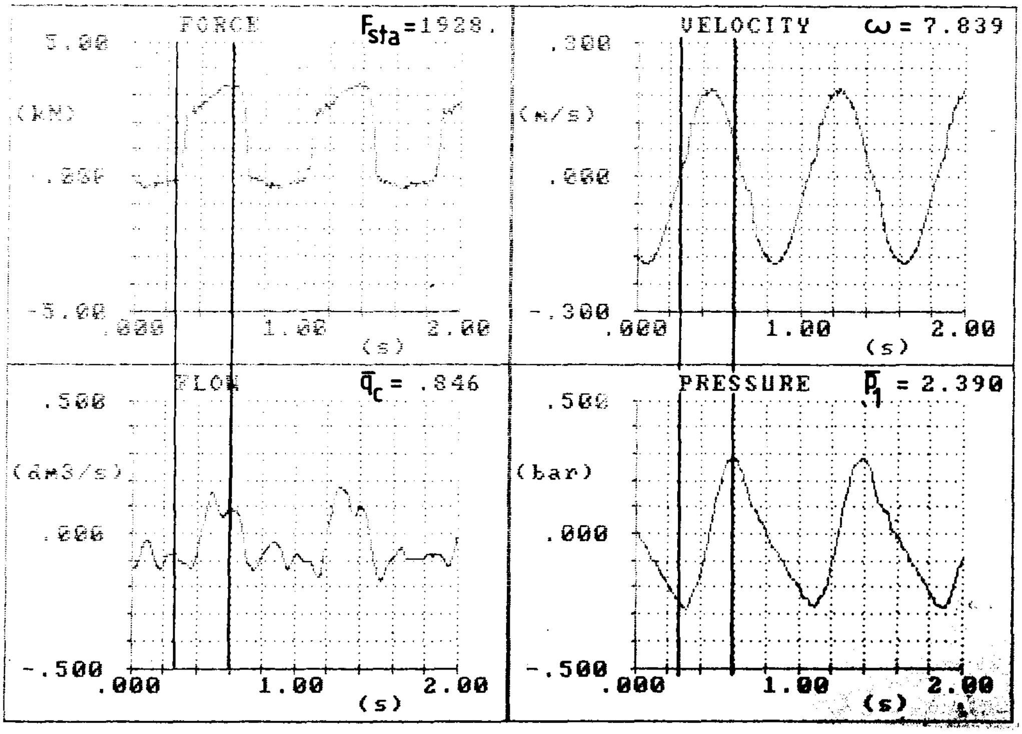


```
                  SUCTION      DELIVERY      PUMP                                 GENERAL

STROKE            0.00E  -1   5.00E  -1   5.00E  -2   RO WATER               1.00E   3
AIRCH/STR VOL     3.40E  -3   4.61E  -3   7.70E  -4   ATM PRESSURE           1.01E   5
LENGTH            7.50E   0   1.04E   2   9.00E  -1   GAS CONSTANT           1.40E   0
DIAMETER          5.30E  -2   3.59E  -2   1.40E  -1   RANGE FORCE Tr/S       3.00E   3
CROSS-SECTION     2.21E  -3   1.01E  -3   1.54E  -2   RANGE FLOW Trans       2.00E   0
HEAD              1.85E   0   1.00E   1   9.20E  -1   TOTAL HEAD             1.28E   1
LAMBDA            2.90E  -2   2.90E  -2   3.00E  -2   STATIC FORCE           1.93E   3
CHI               1.00E   0   5.00E   0   3.94E   1   ONE SAMPLE (ms.)       4.00E   0
R                 5.24E   8   4.34E  10   8.31E   7   NUMBER SAMPLES         5.00E   2
L                 3.40E   6   1.03E   8   9.42E   4                          0.00E  -1
Csystem           1.73E  -8   8.38E  -9   0.00E  -1   AIR SUPPLY             0.00E  -1
wsystem           4.13E   0   1.08E   0   0.00E  -1   ROTATIONAL SPEED       6.37E   0

                  MEAN FLOW    FLOW FLUC    MEAN PRES    PRES FLUC

                  6.74E  -1   1.22E  -1   2.27E   0   2.49E  -1
```



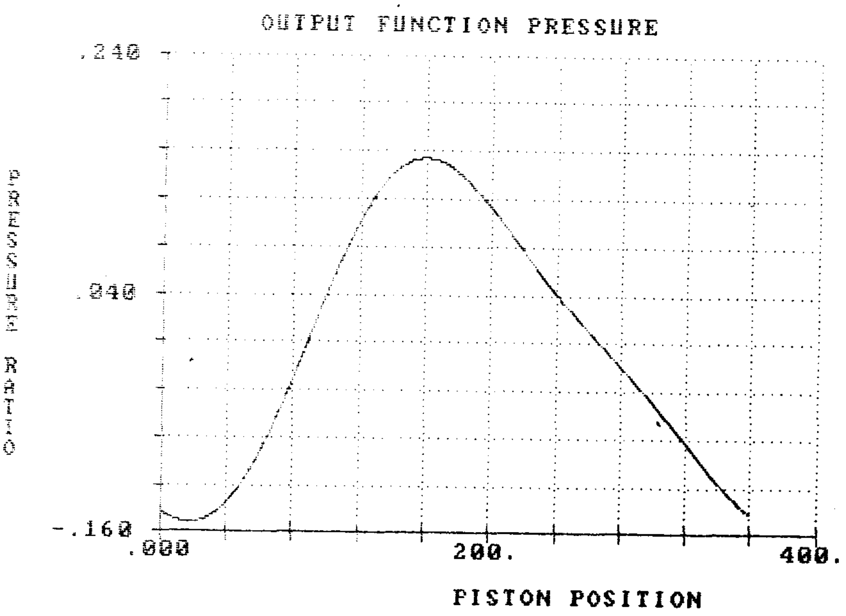
```
Date: 09/22/86          Mean flow:
Exp. number: 9             8.46E  -1
No air supply.          Flow fluct.:
Delivery head:             1.74E  -1
   1.00E   1            Flow ratio:
                           2.06E  -1
Time one sample:        Mean pressure:
   4.00E   0               2.39E   0
Number of samp.:        Pressure fluct.:
         500               2.81E  -1
                        Pressure ratio:
                           1.18E  -1
```

```
THEORY

Mean Pressure:
   2.39E   0
Pressure fluct.:
   3.68E  -1
Pressure ratio:
   1.54E  -1


MEASURED

Mean pressure:
   2.39E   0
Pressure fluct.:
   2.81E  -1
Pressure ratio:
   1.18E  -1
```

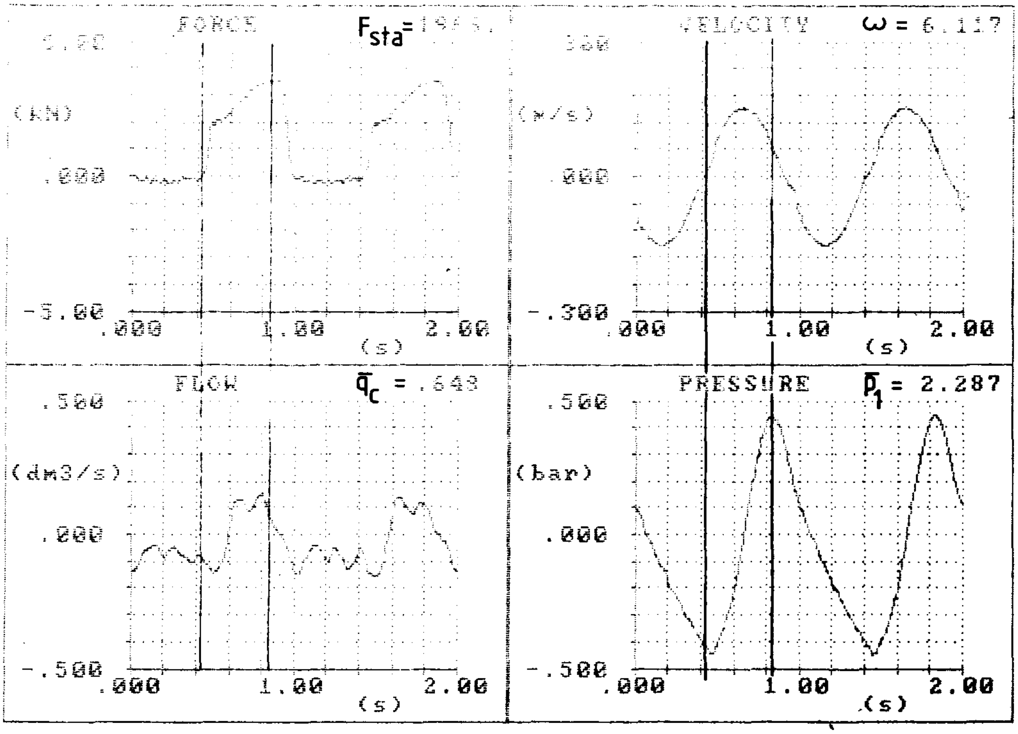


```
                   SUCTION      DELIVERY       PUMP                              GENERAL

STROKE            0.00E  -1    5.00E  -1    5.00E  -2    RO WATER             1.00E   3
AIRCH/STR VOL     3.40E  -3    4.61E  -3    7.70E  -4    ATM PRESSURE         1.01E   5
LENGTH            7.50E   0    1.04E   2    9.00E  -1    GAS CONSTANT         1.40E   0
DIAMETER          5.30E  -2    3.59E  -2    1.40E  -1    RANGE FORCE Tr/S     3.00E   3
CROSS-SECTION     2.21E  -3    1.01E  -3    1.54E  -2    RANGE FLOW Trans     2.00E   0
HEAD              1.85E   0    1.00E   1    9.20E  -1    TOTAL HEAD           1.28E   1
LAMBDA            2.90E  -2    2.90E  -2    3.00E  -2    STATIC FORCE         1.93E   3
CHI               1.00E   0    5.00E   0    3.94E   1    ONE SAMPLE (ms.)     4.00E   0
R                 5.24E   8    4.34E  10    8.31E   7    NUMBER SAMPLES       5.00E   2
L                 3.40E   6    1.03E   8    9.42E   4                         0.00E  -1
Csystem           1.73E  -8    8.38E  -9    0.00E  -1    AIR SUPPLY           0.00E  -1
wsystem           4.13E   0    1.08E   0    0.00E  -1    ROTATIONAL SPEED     7.84E   0

                 MEAN FLOW     FLOW FLUC    MEAN PRES    PRES FLUC

                 8.46E  -1     1.74E  -1    2.39E   0    2.81E  -1
```



Date: 09/22/86
Exp. number: 17
No air supply.
Delivery head:
1.00E 1

Time one sample:
4.00E 0
Number of samp.:
500

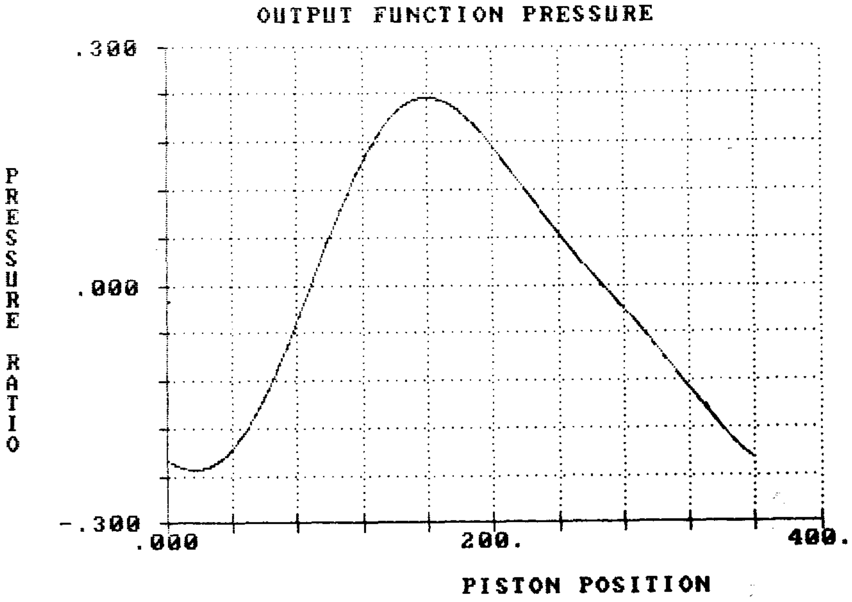
Mean flow:
6.48E -1
Flow fluct.:
1.54E -1
Flow ratio:
2.38E -1
Mean pressure:
2.29E 0
Pressure fluct.:
4.49E -1
Pressure ratio:
1.96E -1

```
THEORY

Mean Pressure:
   2.23E   0
Pressure fluct.:
   6.75E  -1
Pressure ratio:
   3.02E  -1


MEASURED

Mean pressure:
   2.29E   0
Pressure fluct.:
   4.49E  -1
Pressure ratio:
   1.96E  -1
```

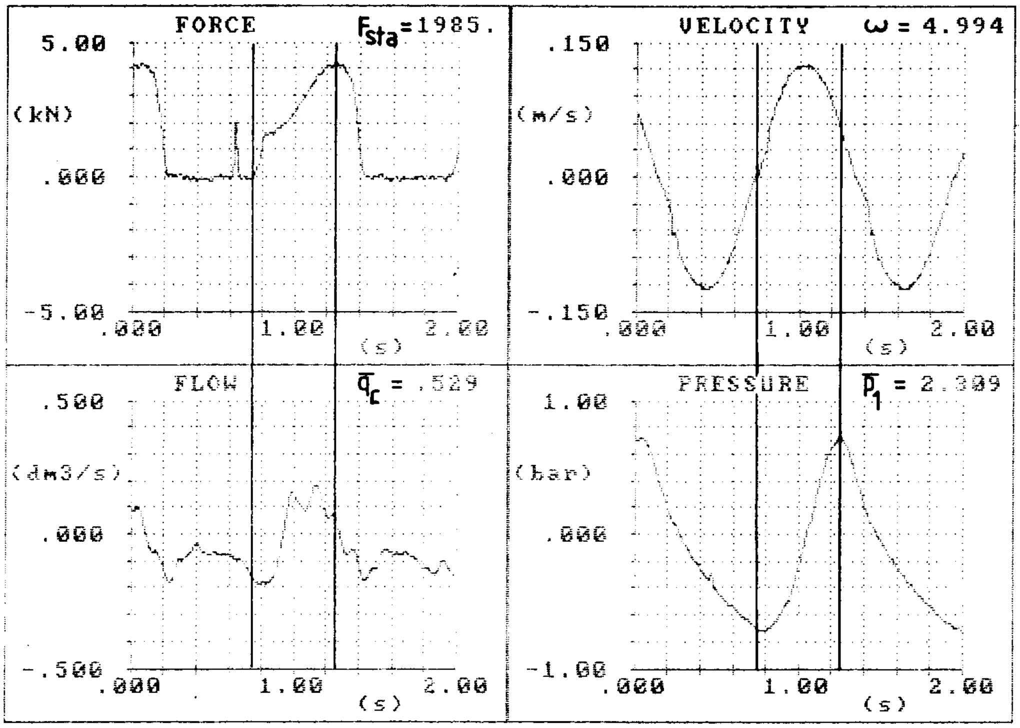


```
                    SUCTION      DELIVERY      PUMP                               GENERAL

STROKE              0.00E  -1    2.50E  -1    5.00E  -2    RO WATER              1.00E   3
AIRCH/STR VOL       3.40E  -3    2.30E  -3    7.70E  -4    ATM PRESSURE          1.01E   5
LENGTH              7.50E   0    1.04E   2    9.00E  -1    GAS CONSTANT          1.40E   0
DIAMETER            5.30E  -2    3.59E  -2    1.40E  -1    RANGE FORCE Tr/S      3.00E   3
CROSS-SECTION       2.21E  -3    1.01E  -3    1.54E  -2    RANGE FLOW Trans      2.00E   0
HEAD                1.85E   0    1.00E   1    1.17E   0    TOTAL HEAD            1.30E   1
LAMBDA              2.90E  -2    2.90E  -2    3.00E  -2    STATIC FORCE          1.97E   3
CHI                 1.00E   0    5.00E   0    3.94E   1    ONE SAMPLE (ms.)      4.00E   0
R                   5.24E   8    4.34E  10    8.31E   7    NUMBER SAMPLES        5.00E   2
L                   3.40E   6    1.03E   8    9.42E   4                          0.00E  -1
Csystem             1.73E  -8    4.19E  -9    0.00E  -1    AIR SUPPLY            0.00E  -1
wsystem             4.13E   0    1.52E   0    0.00E  -1    ROTATIONAL SPEED      6.12E   0

                   MEAN FLOW    FLOW FLUC    MEAN PRES    PRES FLUC

                   6.48E  -1    1.54E  -1    2.29E   0    4.49E  -1
```



**Date: 09/22/86**
**Exp. number: 26**
**No air supply.**
**Delivery head:**
**1.00E 1**

**Time one sample:**
**4.00E 0**
**Number of samp.:**
**500**

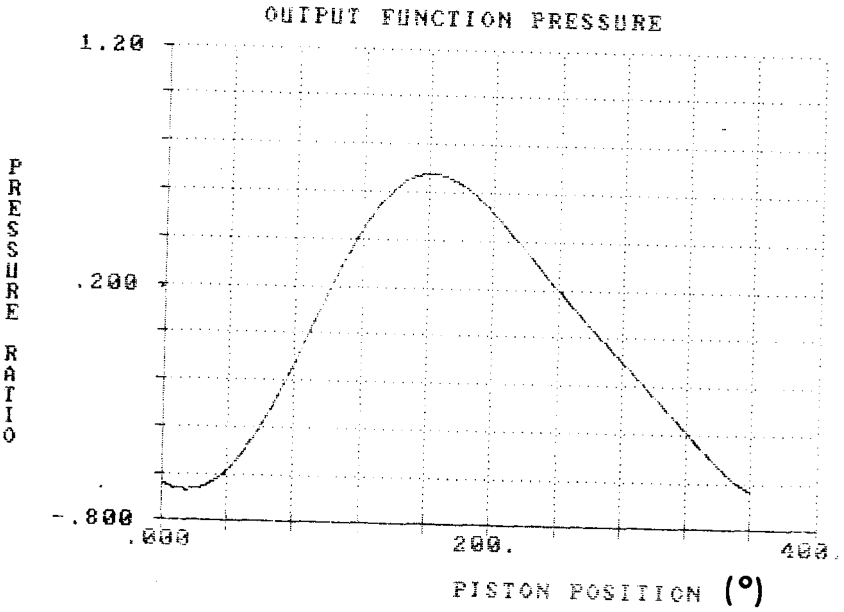
**Mean flow:**
**5.29E -1**
**Flow fluct.:**
**1.84E -1**
**Flow ratio:**
**3.48E -1**
**Mean pressure:**
**2.31E 0**
**Pressure fluct.:**
**7.25E -1**
**Pressure ratio:**
**3.14E -1**

**THEORY**

Mean Pressure:
2.15E 0
Pressure fluct.:
1.46E 0
Pressure ratio:
6.77E -1

**MEASURED**

Mean pressure:
2.31E 0
Pressure fluct.:
7.25E -1
Pressure ratio:
3.14E -1

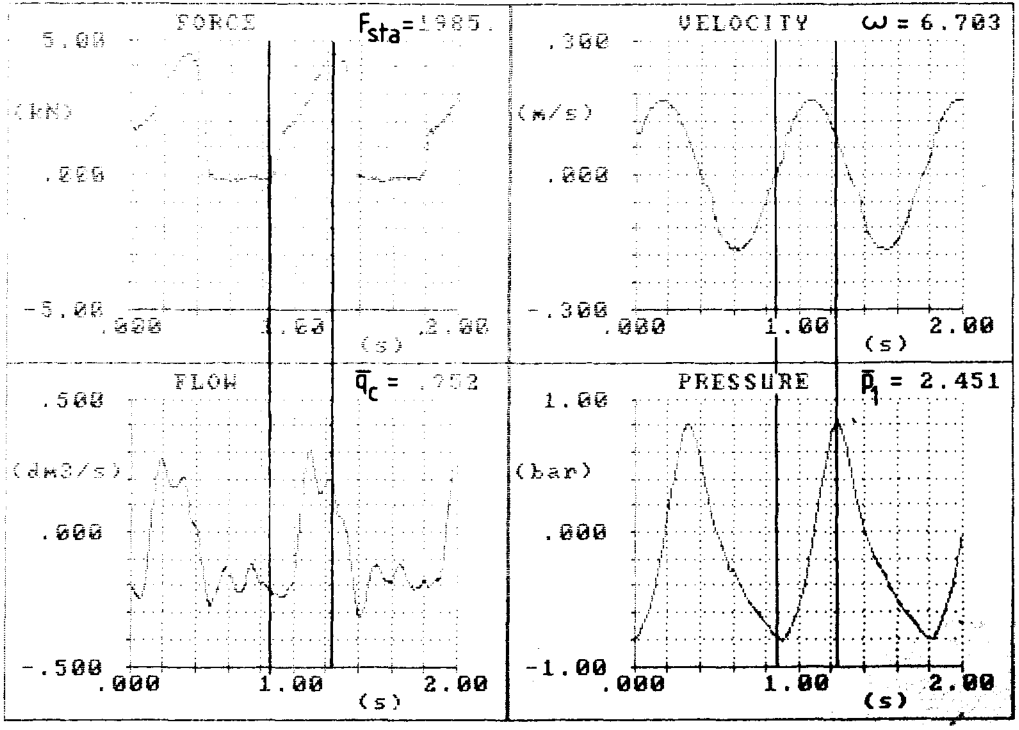


```
                  SUCTION      DELIVERY      PUMP                                GENERAL

STROKE            0.00E  -1    1.25E  -1    5.00E  -2   RO WATER              1.00E   3
AIRCH/STR VOL     3.40E  -3    1.15E  -3    7.70E  -4   ATM PRESSURE          1.01E   5
LENGTH            7.50E   0    1.04E   2    9.00E  -1   GAS CONSTANT          1.40E   0
DIAMETER          5.30E  -2    3.59E  -2    1.40E  -1   RANGE FORCE Tr/S      3.00E   3
CROSS-SECTION     2.21E  -3    1.01E  -3    1.54E  -2   RANGE FLOW Trans      2.00E   0
HEAD              1.85E   0    1.00E   1    1.29E   0   TOTAL HEAD            1.31E   1
LAMBDA            2.90E  -2    2.90E  -2    3.00E  -2   STATIC FORCE          1.99E   3
CHI               1.00E   0    5.00E   0    3.94E   1   ONE SAMPLE (ms.)      4.00E   0
R                 5.24E   8    4.34E  10    8.31E   7   NUMBER SAMPLES        5.00E   2
L                 3.40E   6    1.03E   8    9.42E   4                         0.00E  -1
Csystem           1.73E  -8    2.10E  -9    0.00E  -1   AIR SUPPLY            0.00E  -1
wsystem           4.13E   0    2.15E   0    0.00E  -1   ROTATIONAL SPEED      4.99E   0

                  MEAN FLOW    FLOW FLUC    MEAN PRES   PRES FLUC

                  5.29E  -1    1.84E  -1    2.31E   0   7.25E  -1
```



Date: 09/22/86
Exp. number: 27
No air supply.
Delivery head:
1.00E 1

Time one sample:
4.00E 0
Number of samp.:
500

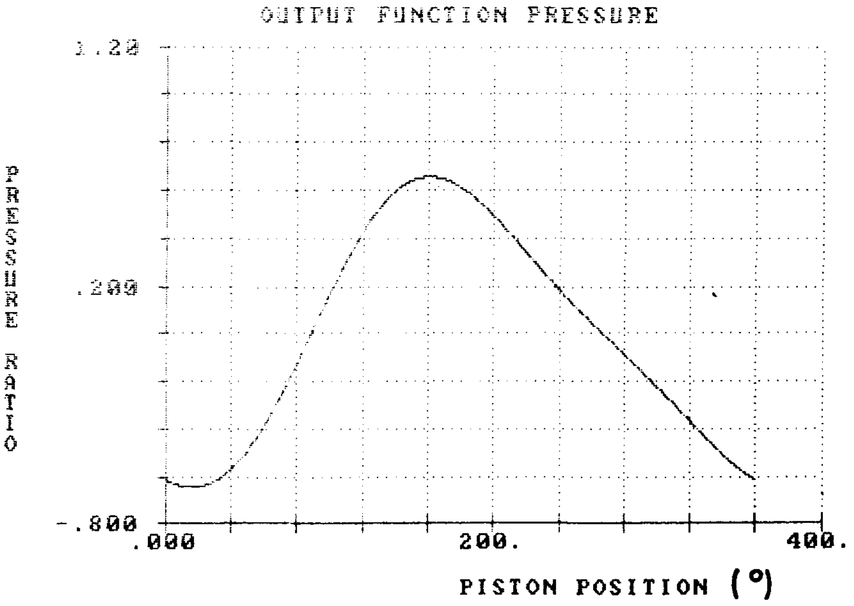
Mean flow:
7.52E -1
Flow fluct.:
3.17E -1
Flow ratio:
4.22E -1
Mean pressure:
2.45E 0
Pressure fluct.:
8.13E -1
Pressure ratio:
3.32E -1

```
THEORY

Mean Pressure:
   2.28E   0
Pressure fluct.:
   1.50E   0
Pressure ratio:
   6.55E  -1


MEASURED

Mean pressure:
   2.45E   0
Pressure fluct.:
   8.13E  -1
Pressure ratio:
   3.32E  -1
```



```
                 SUCTION      DELIVERY      PUMP                                GENERAL

STROKE           0.00E  -1    1.25E  -1    5.00E  -2    RO WATER            1.00E   3
AIRLN/STR VOL    3.40E  -3    1.15E  -3    7.70E  -4    ATM PRESSURE        1.01E   5
LENGTH           7.50E   0    1.04E   2    9.00E  -1    GAS CONSTANT        1.40E   0
DIAMETER         5.30E  -2    3.59E  -2    1.40E  -1    RANGE FORCE Tr/S    3.00E   3
CROSS-SECTION    2.21E  -3    1.01E  -3    1.54E  -2    RANGE FLOW Trans    2.00E   0
HEAD             1.05E   0    1.00E   1    1.29E   0    TOTAL HEAD          1.31E   1
LAMBDA           2.90E  -2    2.90E  -2    3.00E  -2    STATIC FORCE        1.99E   3
CHI              1.00E   0    5.00E   0    3.94E   1    ONE SAMPLE (ms.)    4.00E   0
R                5.24E   8    4.34E  10    8.31E   7    NUMBER SAMPLES      5.00E   2
L                7.40E   6    1.03E   9    9.42E   4                        0.00E  -1
Csystem          1.73E  -8    2.10E  -9    0.00E  -1    AIR SUPPLY          0.00E  -1
wsystem          4.13E   0    2.15E   0    0.00E  -1    ROTATIONAL SPEED    6.70E   0


                 MEAN FLOW    FLOW FLUC    MEAN PRES    PRES FLUC

                 7.52E  -1    3.17E  -1    2.45E   0    8.13E  -1
```

## APPENDIX 6D INACCURACY CALCULATIONS

### THE FLOW

Inaccuracy calculations has no sense because of the unreliability of the flow meter. They are in the same order of the flow fluctuations we expect from the model.

### THE PRESSURE

The measured pressures have an inaccuracy of 1% (calibration) + about 2% (noise signals on the A/D converter) $\simeq$ 3%.

For the transfer function of the dimensionless pressure fluctuations we wrote

$$\frac{\Delta p_1}{\bar{p}_1} = \frac{\gamma}{2\pi}\cdot\frac{\nabla_s}{\nabla_{atm}}\cdot\frac{\bar{p}_1}{p_{atm}} \qquad (6.2)$$

$\dfrac{\gamma}{2\pi}$ : ? (see Appendix 6A)

$\dfrac{\nabla_s}{\nabla_{atm}}$ : $\nabla_s = s\cdot(A_c - A_{pr})$ , $\nabla_{atm} = h_a\cdot(A_c - A_l')$

in which $A_{pr}$ is the cross-section area of the pump rod
$A_l'$ is the cross-section area of the delivery line close to the delivery airchamber.

s: 1 mm / 50 mm = 2%

h: 2 mm / 50, 25 or 12.5 mm = 0.4, 0.8 or 1.6%

$$\frac{A_c - A_{pr}}{A_c - A_l'} : \frac{140 - 16}{140 - 88.5} \Big/ \frac{139 - 16}{139 - 89.3} = 3.5\%$$

$$\overline{\phantom{xxxxxxxxxxxxxxxxxxxx}} +$$

$$\simeq 6.5\%$$

$\frac{\bar{p}_1}{p_{atm}}$ : this is equal to $1 + \frac{\rho g H}{p_{atm}} + \frac{R\bar{q}_c^{\,2}}{p_{atm}}$

$\rho gH$ : 1% (calibration)

$p_{atm}$: 1% (air pressure fluctuations)

$\rho gH/p_{atm} \le 1 \longrightarrow$ inaccuracy $\le 2\%$

$R\bar{q}_c^{\,2}$: R : 3% ($\lambda$ dependant on q, Hilbers [11])

$$\bar{q}_c: \quad \begin{array}{lll} s: & 1/50 & = 2\% \\ A_c: & 1/140 & = 0.7\% \\ \omega: & & < 2\% \\ \hline & 4.7*2 & \simeq 9\% \end{array} \; +$$

$$\begin{array}{l} R\bar{q}_c^{\,2}/p_{atm} \le 0.5 \longrightarrow \text{inaccuracy} \le 6\% \\ \hline \qquad 8\% \end{array} \; +$$

The inaccuracies in fig. 6.1 and 6.2 are:

- horizontal direction: 8%
- vertical direction :15%