Radi Analyzer® and PressureWire®
for constant temperature anemometry

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June 2009
BMTE 09.23

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Eindhoven, June 2009
Abstract

A coronary stenosis can be distinguished from myocardial disease when both local coronary pressure and blood flow are known. The Radi PressureWire® combined with the Radi Analyzer® forms a clinically used configuration for the measurement of local pressure in the coronary arteries. Geven and Van der Horst [5, 8] investigated the PressureWire® for local flow rate measurements and were successful in using the PressureWire® in constant temperature anemometry. They, however, lost the pressure measuring functionality of the PressureWire®-Radi Analyzer® combination.

The aim of this study is to enable anemometry with the PressureWire® through the Radi Analyzer®. For this the Radi Analyzer® was analyzed for constant temperature anemometry purposes. A possible method for constant temperature anemometry was constructed, implemented and investigated by obtaining a calibration relation and tracking a periodic flow signal. However, constant temperature could not be guaranteed and constant temperature anemometry was therefore found impossible with the tested method.
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Chapter 1

Introduction

In coronary artery disease the supply of fresh blood to a part of the heart muscle may be hindered or even impossible by a narrowing of one or multiple arteries of the coronary circulation. The effect of this ranges from pain in the chest, to an ischemia causing heart failure and possible death. For some time it was thought that detection and quantification of arterial narrowings could only be done by X-Ray angiography. In this technique a projection is made of the arteries which have been injected with a contrast agent. By using a projection of the three dimensional situation the severity of the stenosis could easily be over- or underestimated [7, 9]. Besides this limitation, the geometry of the vessel is not the only important factor for proper diagnosis, since it cannot determine the physical flow limiting effects. The severity of the stenosis should be a measure of the limitation of the maximum achievable blood flow due to the stenosis, since this directly indicates the extent of inducible ischemia. Therefore X-Ray angiography is at present not always used for the qualification of the severity of the stenosis. For the diagnosis, morphological information obtained by angiography is found to be less adequate than local physiological parameters like coronary flow and pressure [1, 2, 9, 12]. The trend towards local physiological information has resulted into several pressure and flow based indexes and the accompanying pressure and flow measuring techniques. These sensing devices are based on a guide-wire that is inserted, via the groin. In this study a guide-wire based PressureWire® (PW) (Radi Medical Systems, Uppsala, Sweden) [13] will be used as a flow sensing device. This was previously done by Geven and Van der Horst [5, 8], but they lost the pressure measuring possibility of the PW. It is the aim of this study to enable flow rate measurements with the PW without losing the possibility of pressure measurements.

1.1 Coronary circulation

The heart muscle is almost completely depending on the coronary circulation for perfusion. The two arteries originate from the aorta and have a typical diameter of 3mm. These two
main arteries branch into smaller arteries, arterioles and further down the tree into an interconnected network of capillaries (diameter $5 \mu m$). These capillaries supply the myocardium with nutritious blood and enable the uptake of metabolic waste products which are brought to the right atrium via the coronary veins and through the coronary sinus. Blood flow in the coronary arteries is small during systole compared to blood flow during diastole due to high forces from the heart muscle on the coronary arteries.

**Autoregulation**  In a healthy coronary system the resistance of the larger arteries is negligible compared to the resistance of the microcirculation [12]. Larger arteries can however become locally narrowed or stenosed. This stenosis increases the resistance to blood flow. Autoregulation mechanisms and the growth of collateral arteries can counteract the consequences of coronary arterial narrowing. Both will be briefly discussed. The healthy heart muscle can change its activity when needed, for instance during exercise, causing an extra need for blood perfusion of the myocardium. This perfusion is regulated by the widening of the arterioles, i.e. the smaller arteries between the larger coronary arteries and the microvasculature, caused by the relaxation of the smooth muscle cells inside the arterial wall. This mechanism, which is called autoregulation, can partly compensate for the increase of resistance when the coronary arterial wall gets narrower due to a stenosis. Autoregulation enables continuous flow during the cardiac cycle by continuous changes of the resistance of the arterioles. Therefore no simple relation between coronary pressure and coronary flow exist when autoregulation is active and not at its maximum. When perfusion due to a stenosis can satisfy the demand at rest there may be insufficient reserve left for the increased demand during activity; the autoregulation reserve is limited. When the full autoregulation reserve is used the diameter of the arterioles cannot increase anymore.

**Collateral arteries**  Besides autoregulation, the growth of collateral arteries may compensate for the increased resistance due to a stenosis in the coronary circulation. Collateral arteries are natural bypasses, creating a new connection between coronary arteries when obstruction in these arteries are present and functionally significant.

**Adequate diagnosis**  Functional factors such as the extent of the myocardial perfusion area of the diseased artery, the presence of collateral flow and the resistance of the microvascular bed are important for an adequate diagnosis. Since angiography cannot provide an adequate measure for the severity of the stenosis, qualitative physiological information on the state of the coronary circulation should be provided. These physiological factors are the pressure and flow.
Model of the coronary circulation and FFR  To gain insight in the functioning and shortcomings of the diagnostic indexes used in practice, the coronary circulation is modeled as a system of variable resistors, in serie and parallel, under variable pressure. An upcoming diagnostic index is the Fractional Flow Reserve (FFR) [14] which can be measured with the PW. The FFR index compares the maximum achievable flow with a stenosis compared to the maximum flow without the stenosis and is therefore a direct indicator of the severity of the stenosis. For this index the PW is used in order to get the information that quantifies the amount of flow by measuring pressure. The FFR index can be explained with a schematic of the model for a coronary artery stenosis, see figure 1.1.

Figure 1.1: This graphical representation of the coronary artery model shows the aorta, the stenotic coronary artery, the possible collateral, the myocardial tissue circulation and the venal part ending in the right atrium RA. This model aims at a description of the myocardial perfusion and its (possibly partly obstructed) input flows. In the absence of the collateralarterie the myocardial perfusion, Q, is determined by the pressure difference between the arterial pressure, \( P_{ao} \), and the venous pressure, \( P_V \) divided by the sum of the myocardial resistance, R, and the resistance cause by the stenosis in the coronary artery, \( R_S \). The distal coronary pressure is the coronary pressure distal to the stenosis and \( Q_S \) the blood flow through the supplying epicardial coronary artery. If collateral arteries are present the blood flow through the myocardial bed is the sum of collateral blood flow, \( Q_C \), and \( Q_S \). The resistance of the collateral artery is \( R_C \).

In the coronary artery circulation model the resistance due to stenosis \( R_S \), the possible collateral arteries \( R_C \) and the myocardial bed resistance \( R \) are taken into account in the modeling of the parameter of interest: the perfusion of the myocardial bed \( Q \). In a normal functioning heart muscle these resistances are not considered to be constant. This chain of parallel and serially coupled resistors is loaded by the arterial pressure, \( P_{ao} \) from the aorta on the one side and the venous pressure \( P_V \) on the other side. In between there is the pressure distal to the stenosis, \( P_D \). For the FFR index, collateral flow \( Q_C \), is absent and myocardial perfusion equals the blood flow through the supplying epicardial coronary artery.
By definition FFR is:

\[
FFR = \frac{Q_{\text{max}}}{Q_{\text{max}}^N},
\]  

(1.1)

where \(Q_{\text{max}}\) is the maximal flow with stenosis and \(Q_{\text{max}}^N\) the maximal flow in the hypothetical case without stenosis. This hypothetical case can easily be measured since the pressure distal to the stenosis in the hypothetical case, in which the stenosis has zero resistance, equals the aortic pressure \(P_{ao}\). The flow can be written as the pressure difference divided by the resistance, \(Q_{\text{max}}\) and \(Q_{\text{max}}^N\) are:

\[
Q_{\text{max}} = \frac{P_d - P_v}{R},
\]  

(1.2)

\[
Q_{\text{max}}^N = \frac{P_{ao} - P_v}{R},
\]  

(1.3)

where \(P_{ao}, P_d\) and \(P_v\) are the arterial, distal and venous mean pressures and \(R\) the myocardial resistance at maximal vasodilation. If \(P_v\) is assumed to be zero, which it generally is [12], FFR can be expressed as the ratio of distal to arterial pressure:

\[
FFR = \frac{P_d}{P_{ao}}.
\]  

(1.4)

According to a clinical trial performed by Tonino et al. [14] routine measurement of FFR, additional to angiography, was found to improve the outcome of patients with multivessel coronary artery disease undergoing coronary angioplasty (Dottering) with drug-eluting stents. The PW is used in these FFR measurements.

1.2 Pressure measurements with the PW-RAN combination

The PW is operated by the Radi Analyzer® (RAN) [13]. The RAN also presents the pressure data to the physician, see figure 1.2(a). The PW-RAN measuring system can, for explanatory purposes, be reduced to a Wheatstone bridge composed of a pressure sensitive resistor, temperature compensating resistor and two precision resistors, as depicted in figure 1.2(b).

The sensor of the PW is composed of a strain gauge, \(R_A\), measuring pressure and a glued strain gauge, \(R_P\), independent on pressure but with the same temperature dependency as the pressure sensing element. A temperature corrected pressure signal is obtained by measuring the voltage difference over the Wheatstone bridge as depicted in figure 1.2(b). For the completion of the Wheatstone bridge two reference resistors with a fixed value
(a) The Radi PressureWire® and Radi (b) Schematic of the Radi pressure reading Analyzer® in the back.

Figure 1.2: (b) A Wheatstone bridge is used to measure the pressure with temperature compensation. $R_A$ and $R_P$ are the only parts inside the PressureWire® sensor, the rest of the bridge is outside the sensor (and outside the body). $R_A$ is a pressure sensitive element but also influenced by temperature, $R_P$ is a temperature sensitive element with which the pressure signal is corrected for temperature. The $R_B$ resistors are fixed precision resistors. The pressure signal, $V_{ex}$, is linearly dependent on pressure differences and on the excitation voltage $V_{ex}$. The excitation voltage is kept constant during a pressure measurement.

are placed in the circuit powered by the excitation voltage source $V_{ex}$. The temperature corrected pressure signal, $V_P$, can be computed as:

$$V_P = V_{ex} \cdot \left\{ \frac{R_A}{R_B + R_A} - \frac{R_P}{R_B + R_P} \right\}. \quad (1.5)$$

Now, the actual pressure can be computed using a calibration relation that is experimentally determined for each sensor. If one assumes this relation to be linear the actual pressure, $P$, is computed as:

$$P = V_P \cdot a + b, \quad (1.6)$$

where parameters $a$ and $b$ are obtained with the calibration procedure. The strain gauge and glued strain gauge are modeled as a superposition of a reference value, pressure effects and temperature effects, where pressure effects are zero for the glued strain gauge:

$$R_A = R_{A0} + \frac{\partial R_A}{\partial T} (T - T_0) + \frac{\partial R_A}{\partial P} (P - P_0), \quad (1.7)$$

$$R_P = R_{P0} + \frac{\partial R_P}{\partial T} (T - T_0), \quad (1.8)$$

with $P_0$ and $T_0$ the pressure and temperature at which $R_{A0}$ and $R_{P0}$ were determined.
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Figure 1.3: Sketch of the method of thermodilution. A cold fluid is ejected from a catheter and creates a temperature drop in the fluid which can be detected by a temperature sensitive sensor such as the PressureWire®. By this method the mean flow can be detected.

1.3 Flow measurements with PW

Although the PW was developed for measuring coronary artery pressure, research has been carried out to investigate its use in the flow measuring techniques continuous thermodilution and thermoconvection or Constant Temperature Anemometry (CTA).

1.3.1 Thermodilution

With continuous thermodilution the absolute blood flow is assessed by a continuous injection of cold saline solution into the coronary artery. This cold solution is transported downstream with blood flow where it is detected by the temperature sensing element on the tip of the PW. Assuming complete mixing, the temperature of the saline/blood solution is a measure of the mean flow.

When a bolus injection is used, the mean transfer time between the bolus injection and the detection of a temperature difference downstream, can be used to measure mean flow [1]. Due to the necessity of an injection pump and infusion catheter in the catheterization room the whole procedure is not user friendly.

1.3.2 Constant temperature anemometry

Geven and Van der Horst [5, 8] investigated the use of the PW as a constant temperature anemometer. The temperature sensitive resistor inside the PW sensor created the possibility for anemometry in the coronary artery. In this method the temperature of the sensor is controlled to be in an equilibrium state above ambient temperature. In order for this condition to hold, the amount of heat being lost to the blood passing the sensor should be balanced with the amount of heat generated by the components of the sensor. In this method the amount of heat transferred to the blood depends on the flow [5, 8]. Therefore, the power put into the PW is a measure for the flow passing the PW tip. By using the PW as an anemometer Geven and Van der Horst [5, 8] succeeded in measuring
coronary-simulating flow in an in-vitro setup but also in tracking the coronary flow in pigs [5].

They, however, lost the pressure measuring functionality of the PW. In this project it is investigated how the anemometry mechanism for the PW could be built into the RAN with which pressure measurements are controlled, in order to use the PW in both the anemometry and pressure mode simultaneously. The goal of this report therefore is to enable anemometry with the PW through the RAN. For the sake of pressure measurements and possible clinical implementation it is strived to change the software of the RAN only.

Principle

In Constant Temperature Anemometry (CTA) a temperature dependent resistor is heated and the temperature is controlled to be constant. Heat transfer will take place between the heated resistor and the colder surrounding fluid. When the fluid is passing the resistor, more power is needed to keep the sensor at constant temperature; the power needed for a constant temperature is a measure for the velocity passing the fluid. In the next section the physics behind this process is briefly discussed. For more information on this topic the reader is referred to [3, 5]. In a sensor, which is in thermal equilibrium with the surrounding fluid, all the energy dissipated from the passive resistor will be transferred into the surrounding fluid. The heat flux is equal to the power dissipated in \( R_p \). This heat transfer is assumed to be totally convective and the heat flux can be described by Newton’s law of cooling:

\[
q'' = h(T_s - T_w),
\]

where \( q'' \) is the convective heat flux (W/m\(^2\)). The convective heat flux is proportional to the difference between the sensor’s temperature \( T_s \) and the surrounding fluid temperature \( T_w \). The parameter \( h \) (W/m\(^2\)·K) is the convective heat transfer coefficient. This parameter depends on the conditions of the boundary layer, which are influenced by the geometry, the nature of the fluid motion and a collection of fluid thermodynamics and transport properties. If the sensor’s geometry is constant, \( h \) will be some universal function of the location on the sensor and the dimensionless Reynolds and Prandtl numbers. In hot wire anemometry \( h \) is the following function of the flow rate \( (Q) \):

\[
h = a + b \cdot \left( \frac{Q}{Q_0} \right)^n,
\]

where \( a, b \) and \( n \) are parameters and \( Q_0 \) a reference flow. Since \( R_P \), the heat transfer surface \( A \) and the temperature difference are assumed to be constant, the voltage over \( R_P \) can be written as a function of the flow rate:

\[
V_P^2 = K_0 + K_1 \cdot \left( \frac{Q}{Q_0} \right)^n,
\]

where \( V_P \) is the voltage over the passive resistance and \( K_0, K_1 \) and \( n \) are parameters that can be derived experimentally. Equation 1.11 is the basis of CTA, since it relates the power applied to maintain a constant temperature to the flow rate of the surrounding fluid.
14

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Figure 1.4: Schematic of the PW as an anemometer. The pressure sensitive side is cut of and a new Wheatstone bridge is formed by adding another fixed resistor $R_B$ and an adjustable resistor $R_T$. Now the voltage difference is not used as a readout signal but used as an error signal in a negative feedback system (composed of the Operational Amplifier (OpAmp) with amplification factor $K$) which ensures that the resistance of $R_P$ equals that of $R_T$. With the added adjustable resistor $R_T$ the temperature of the sensor can be changed to be at a fixed value above ambient temperature. The power needed to keep this temperature fixed is a measure for the flow rate flowing over passing the sensor.

Figure 1.5: Extended schematic of the PW-RAN combination for temperature corrected pressure measurements. With respect to figure 1.2(b) an extra signal, $V_T$, is obtained that is a subtraction of an adjustable voltage, $V_T^*$, and the voltage, $V_{BP}$, on the branch of the temperature sensitive resistor. For constant $T^*$, $V_T^* = \alpha \cdot V_{EX}$.

1.3.3 PW anemometry without RAN; previous work

Geven and Van der Horst [5, 8] used the PW, without the RAN, to track coronary flow signals by exploiting the temperature dependency of the glued strain gauge in the sensor. By adding two extra resistors, of which one is adjustable, and an Operational Amplifier (OpAmp) for negative feedback, they created the standard method for anemometry. The negative feedback ensures a constant temperature of the glued strain gauge, of which the resistance equals the chosen resistance $R_T$ by adjusting the voltages exciting the bridge. A schematic of this can be found in figure 1.4.

1.3.4 PW anemometry with RAN

The pressure sensitive branch, figure 1.4, of the PW is disconnected in the anemometry proces, thereby disabling pressure measurements. When looking at a more extended model of the pressure measuring for the PW, see figure 1.5, it can be seen that the situation in
the PW-RAN combination is similar to the situation shown in figure 1.4 with respect to anemometry but with the exception of the negative feedback loop, not present in the PW-RAN combination. The extra signal that is obtained is the temperature signal $V_T$, which is also a subtraction of two voltages of which one is linearly dependent on $V_{EX}$, i.e. $V_{T*}$, and the other, $V_{BP}$, also temperature dependent. The temperature signal in figure 1.5 can be used in the same way as the error signal in figure 1.4. The anemometry functionality of the PW-RAN combination will be investigated based on this similarity. For this the temperature signal $V_T$ will be fed back to the excitation voltage $V_{EX}$ by the mediation of a feedback algorithm lodged on a PC.

1.4 Outline

According to the above the PW-RAN combination has the potential for CTA when a feedback algorithm is implemented in the existing situation. To create this extra functionality in the RAN research steps are formulated and answered analytically or experimentally.

**Sampling frequency** Using the PW-RAN combination to measure flow has the advantage that pressure measuring functionality of the PW is not lost. However, by using the RAN the temperature signal should be digitized and the sampling frequency must be sufficient for tracking the coronary artery flow signal. It should be investigated whether the sampling frequency of the RAN is sufficient for coronary flow tracking.

**Power** The RAN should be able to supply enough power to obtain the overheat temperature of $15^\circ C$, which gave good sensitivity for Van der Horst [8].

**Pressure switch** In the flow measurement of Geven and Van der Horst [5, 8] the pressure sensitive side was not excited by $V_{EX}$, it should be investigated, by means of experiment, if this is a necessary condition to make flow measurements possible or if excitation of the pressure sensitive side does not influence the flow tracking.

**RAN verification** The internal network of the RAN is complicated and the schematic in figure 1.4 is the simplification used in this research. This simplified model of the PW-RAN, is to be tested by constructing a Simple ANalyzer (SAN) with the simplified model of the RAN as its design.

**Temperature signal** The dependence of the system on the temperature signal must be analyzed analytically in order to understand the outcome of the experiments for the Pressure switch and SAN and to compute the necessary voltage for sufficient Power.

**Control** For CTA the temperature of the sensor should be controlled constant by keeping the temperature signal constant. For this a controlling process must be designed and implemented.
**Static flow calibration** In order to obtain a relationship between power and static flow, the sensor must be calibrated.

**Dynamic performance** Since the flow sensor will be used to track coronary artery flow, the dynamical behavior of the sensor is to be investigated.

These research steps will be the next step in achieving the final goal of using the PW-RAN combination in simultaneous pressure and flow measurements.
Chapter 2

Materials and Methods

2.1 Materials

2.1.1 Radi PressureWire®

The Radi PressureWire® Certus is a sensor tipped guide-wire with a working length of 175cm and a 0.355mm diameter and can be connected to a Radi Analyzer® (RAN). The sensor is located 3cm proximal to the end of a guide-wire, see figure 2.1(a). The sensor consists of a silicon chip placed inside a cavity, see figure 2.1(b), and the main components are a temperature and pressure resistor, from now on referred to as the passive and the active resistor, abbreviated by \( R_P \) and \( R_A \), respectively, and with a typical value of 2700Ω. The active resistor is a strain gauge mounted on a membrane which deforms under pressure but is also temperature dependent. Temperature effects on pressure readings are, partly, compensated for by \( R_P \). Table 2.1 displays the minimal, typical and maximal values of the parameters in the PW-RAN combination. The cable resistance \( R_C \) is assumed constant for as long as temperature differences along the wire are constant.

Table 2.1: Parameters of the Radi PressureWire® and RAN resistors, namely the active, passive and common resistor with their temperature dependency. For the active resistor the pressure dependency is given. \( R_B \) is a precision resistor inside the RAN. Unknown parameters have been indicated with a [-].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Min</th>
<th>Typical</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_A )</td>
<td>Ω</td>
<td>200</td>
<td>2700</td>
<td>3200</td>
</tr>
<tr>
<td>( R_P )</td>
<td>Ω</td>
<td>200</td>
<td>2700</td>
<td>3200</td>
</tr>
<tr>
<td>( R_C )</td>
<td>Ω</td>
<td>-</td>
<td>41.5</td>
<td>-</td>
</tr>
<tr>
<td>( R_B )</td>
<td>Ω</td>
<td>-</td>
<td>2490</td>
<td>-</td>
</tr>
<tr>
<td>( \delta R_A )</td>
<td>ppm</td>
<td>400</td>
<td>500</td>
<td>-</td>
</tr>
<tr>
<td>( \delta R_P )</td>
<td>ppm</td>
<td>400</td>
<td>500</td>
<td>-</td>
</tr>
<tr>
<td>( \delta R_C )</td>
<td>ppm</td>
<td>-</td>
<td>3930</td>
<td>-</td>
</tr>
<tr>
<td>( \delta P )</td>
<td>mmHg</td>
<td>7.9</td>
<td>10</td>
<td>-</td>
</tr>
</tbody>
</table>
2.1.2 Radi Analyzer®

The RAN processes the pressure signal obtained from the PW and visually presents the pressure data. Before reading the pressure signal the RAN calibrates the sensor and corrects for temperature and pressure. During the measurement phase the RAN will excite the sensor with an excitation voltage ($V_{EX}$), as depicted in figure 1.2(a) and figure 1.5. $V_{EX}$ is 2V for a pressure reading and for testing purposes it is 4V maximum. The RAN has two receiving and two transmitting optical ports which can be used for communication. One pair will be used in communication with Labview (Labview 7.1, National Instruments, Austin, Texas) and the other, which is more user friendly, for communication outside the Labview program. The analog signals from the PW-RAN combination are digitized with Analog to Digital Converters (ADC) for further processing. The update rate inside the (digital) RAN is 2kHz.

2.2 Methods

To implement the constant temperature mechanism in the PW-RAN combination, in order to mimic the analog circuit used by Geven and Van der Horst [8, 5], a temperature dependent signal should be controlled. In their system this was achieved by a negative feedback controlled Wheatstone bridge, as seen in figure 1.4, and according to the schematic shown in figure 1.5 similar operation could be guaranteed by adding an OpAmp in the software connecting the temperature signal $V_T$ and the excitation voltage $V_{EX}$. It must, however, be analyzed whether this suggested construction will make constant temperature anemometry possible. Furthermore it will be analyzed if the RAN can give the sampling frequency needed for digital CTA and if the RAN can deliver sufficient power for CTA.
Figure 2.2: (b) Schematic of the Radi Analyzer®. When connected with the PW, connection points $Pw_1$ and $Pw_2$, and excited with $V_{EX} = 2V$, temperature corrected pressure can be obtained in $V_P$ and a temperature signal from $V_T$. Inside the RAN the analog signals, like $\tilde{V}_T$ and $\tilde{V}_P$ are digitized and become $|\tilde{V}_T|$ and $|\tilde{V}_P|$. Both $R_B$ resistors are the same precision resistors and with $T^*$ the voltage $V_{T^*}$ is adjustable for calibration purposes.

The construction of the software that will connect the temperature signal to the bridge excitation voltage will also be discussed. In the end of the methods section the research question that will be answered by experiment are dealt with, experimental design will be given.

2.2.1 Analysis

Temperature signal, $V_T$

Together with the PW the RAN forms a bridge structure which is depicted in figure 2.3. The model in this figure only includes the components used in this research. It is composed of two branches that are excited by $V_{EX}$ and a voltage differentiator that reads the voltage difference between the voltage on the temperature sensitive branch and a reference voltage. $R_A$ and $R_P$ are on the sensor of the PW and $R_C$ is the resistor of the microcable that connects the sensor to the RAN, the rest of the circuit is within the RAN. In a pressure measurement the $V_T$ reading is used to measure the temperature. This temperature signal is a subtraction of the temperature offset voltage $V_{T^*}$ from the voltage at the passive side of the bridge $V_{BP}$,

$$V_T = V_{T^*} - V_{BP}.$$ (2.1)

Experiments showed that $V_{T^*}$ is proportional to $V_{EX}$ at constant value of the temperature offset value ($T^*$):

$$V_{T^*} = \alpha V_{EX}|_{T^*=cst},$$ (2.2)
Figure 2.3: Electric schematic of the PW-RAN bridge for CTA. The $R_A$ and $R_P$ are respectively the active and passive resistors in the PW sensor. The $R_C$ is the resistance of the microcable. The rest of the elements are within the RAN. Such as the two precision resistors $R_B$. $V_{EX}$ is the excitation voltage that is put over the bridge. $V_T$ is the temperature signal of the system. The $V_{T*}$ is the temperature offset voltage dependent on the temperature offset value $T^*$. For constant $T^*$, $V_{T*}$ is proportional to $V_{EX}$ with proportionality parameter $\alpha$.

where $\alpha$ is a constant. $V_{BP}$ is the sum of the voltage over $R_C$ and $R_P$ and can be written as:

$$V_{BP} = I_P R_P + I_C R_C,$$  

(2.3)

where $I_P$ is the current through the passive branch and $I_C$ is the current through the common branch, or the total current. According to Ohms law, $I_C = V_{EX}/R_{tot}$, where $R_{tot}$ is the total resistance that can be written as:

$$R_{tot} = R_C + \frac{(R_A + R_B)(R_P + R_B)}{(R_A + R_B) + (R_P + R_B)}.$$  

(2.4)

Now the temperature reading $V_T$ can be rewritten into:

$$V_T = V_{EX} \cdot \left\{ \alpha - \left( \frac{R_P}{R_P + R_B} - \frac{R_C}{R_{tot}} \left( \frac{R_P}{R_P + R_B} + 1 \right) \right) \right\}.$$  

(2.5)

In the system used by Geven and Van der Horst [5, 8] the temperature signal was zero
by means of the negative feedback loop ensuring a constant value of $R_P$:

$$V_T = V_{EX} \cdot \left\{ \alpha - \left( \frac{R_P}{R_P + R_B} - \frac{R_C}{R_{tot}} \left( \frac{R_P}{R_P + R_B} + 1 \right) \right) \right\} = 0$$

$$V_{EX} = 0 \vee \left\{ \alpha - \left( \frac{R_P}{R_P + R_B} - \frac{R_C}{R_{tot}} \left( \frac{R_P}{R_P + R_B} + 1 \right) \right) \right\} = 0,$$

(2.6)

Non-trivial solution: $R_P = R_B \frac{-(\alpha - \frac{R_C}{R_{tot}})}{(\alpha - 1)}$.

In the non-trivial case, which can be obtained by a non-zero initial $V_{EX}$, $R_P$ is constant, when ignoring the small effect of the change on $R_{tot}$ caused by pressure changes.

A similar mode of operation is not possible with the PW-RAN system due to a problem in digitizing the analog signal. The temperature offset value ($T^*$), which is directly related to $\alpha$, is used in order to obtain an unsaturated temperature signal $\left| V_T \right.$.

Alternatively, $\left| V_T \right.$ will therefore be controlled at a constant nonzero level which has to be determined for each sensor. This reference point should be chosen such that the input signal can pass the Analog to Digital Converter (ADC) unsaturated within the voltage range of 0V to max voltage, which is 9V for the adjusted Analyzer. The reference point is chosen such that the sensor has an overheat of 15°C. By controlling at a nonzero level equations 2.6 do not longer hold, control is, however, still possible.

$V_{EX}^2$ as a measure for CTA Exciting both the passive and the active side of the PW-RAN bridge still allows for CTA application of the PW-RAN combination. The power dissipation of the passive side of the PW-RAN bridge is, however, not the only contribution to the heat dissipated by the sensor, since the active side also produces heat with $R_A$. This extra contribution has to be taken into account in the computation of the power dissipated in the sensor.

During CTA the temperature of the sensor is kept constant, the power dissipated in the passive side and the active side $P_{RP}$ and $P_{RA}$ then balances the amount of energy being lost to convection. The total power dissipated is a measure for the flow rate, see section 1.3.2, and can be computed from:

$$P_{total} = P_{RP} + P_{RA} = \left\{ \frac{R_P}{R_B + R_P} + \frac{R_A}{R_B + R_A} \right\} \cdot V_{EX}^2,$$

(2.7)

neglecting effects from the cable resistance. In this research pressure dependency is neglected during CTA and the first part of equation 2.7 becomes constant. The power law of equation 1.10 can therefore be divided by a constant and a flow-$V_{EX}^2$ relation can be found.
Chapter 2. Materials and Methods

Figure 2.4: Characteristic left coronary blood pressure and flow curves.

**Sampling frequency**

The periodic coronary artery flow signal can be characterized by a Fourier-series. The number of functions in a series depends on the characteristics of interests in the signal, for this design frequency components up to 25Hz are evaluated. Control theory demands a controlling system 20 times as fast as the highest frequency in the signal that is to be obtained [4]. The sampling frequency of the controller should be 500Hz in order to track the coronary artery flow signal adequately. The 2kHz update rate of the RAN is therefore sufficient for tracking the flow signal by CTA. The CTA algorithm will not be implemented in the RAN during the developing and testing period, but on an external computer communicating with the RAN. However, communication between the RAN and the computer gives a time delay between 12ms and 30ms, thereby decreasing the maximum traceable frequency during this research to 2Hz.

**Power**

The maximum voltage supplied by the RAN cannot give the power Van der Horst [8] needed for an overheat of 5°C, whereas 15°C is the preferred overheat temperature. It can therefore be concluded that the RAN cannot be used in a CTA measurement without adjustment. If the excitation voltage is doubled, the power dissipation will be in between the power Van der Horst needed in order to get 10°C and 20°C overheat. From this it can be concluded that a gain of two in \( V_{EX} \) will generate enough power for a sufficient overheat, the RAN with doubled maximal excitation voltage is called the Adjusted RAN and will be used in the CTA experiments.
2.2.2 Control design

Figure 2.5: This picture shows the total CTA schematic. The PW is connected to the RAN. Within the RAN both a Analog to Digital converter is present (for the signals coming from the PW) and a Digital to Analog converter (for the signals going to the PW). The RAN sends the temperature signal to the controlling unit. The error is calculated and the controller sends out a new excitation voltage to the RAN.

A schematic for the digital system used for CTA is depicted in figure 2.5. The RAN sends the temperature signal from the PW to the controller. The difference between the actual and the target temperature value is the error for which must be compensated by the controller by means of the control signal \( V_{EX} \).

The controlling system used in this research can be expressed as:

\[
V_{EX} = \left( K_p \epsilon + K_i \int \epsilon dt \right) \cdot Q_f. \tag{2.8}
\]

This is a Proportional gain controller with Integration or a PI controller. The proportional gain of the controller multiplies the contemporary error with a constant \( K_p \). The integral part of the controller multiplies the sum of all the previous errors with a constant \( K_i \). These constants can be determined with the use of methods like root locus or lead lag design and trial and error. The first two methods require knowledge on the frequency response on the system. In this research an estimation of the control parameters were obtained by the last method. The Quantity Factor \( (Q_f) \), translates the temperature signal into a voltage. The control algorithm with \( V_T \) as the input and \( V_{EX} \) as the output was implemented in Labview.
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2.2.3 Experiment design

Pressure switch

The Radi Analyzer Xpress is a new model of the RAN with the possibility of switching off the pressure branch, this functionality is shown in figure 2.6. In the experiments of Geven and Van der Horst [5, 8] the active side was not excited, but it will be examined if this is necessary for flow measurements.

An experiment will be conducted with the RAN Xpress and a pseudo PW in order to investigate the difference of the opening of the switch. In the pseudo PW the PW is replaced by two fixed resistors, independent of pressure and temperature. From equation 2.5 $V_T$ is expected to be linearly proportional to $V_{EX}$. The RAN Xpress will be tested with the pseudo PW for the open and closed configuration of the pressure side of the bridge by stepwise increase of $V_{EX}$. Based on this experiment a choice is made whether or not to excite also the active side. $V_T$ will be measured at $V_{EX} = [1V - 4V]$, it will be tested which configuration, pressure switch on or off, follows the predicted behavior, of a linear relation with respect to $V_{EX}$, best.

RAN verification

The simplified model of the PW-RAN, as depicted in figure 1.4, is to be tested by constructing a Simple Analyzer (SAN) with the simplified model of the RAN as its design. The schematic of the SAN is depicted in figure 2.7. In the experiment the behavior of the temperature signal $V_T$ at increasing excitation voltage, $V_{EX}$, of two PW’s is compared for the RAN and the SAN. After each excitation step the PW is unexcited for 3s in order to cool down. The PW’s will be tested in air at room temperature. The PW-RAN combina-
Figure 2.7: Electric schematic of the PW SAN bridge. \( R_P \) is the passive resistor in the PW sensor, \( R_C \) is the resistance of the microcable. The rest of the elements are within the SAN. Such as the two precision resistors \( R_B \). \( V_{EX} \) is the excitation voltage that is put over the bridge. \( V_T \) is the temperature signal of the system and the \( R_T \) is used to balance the bridge.

Static calibration

In order to obtain a relationship between \( V^2_{EX} \) and static flow as depicted in equation 1.11, the sensor should be calibrated. For this a PW-RAN combination with controlled temperature signal is subjected to different flow rates while obtaining the voltage needed to satisfy the control condition. The experiment is conducted for 10s with a sample period of 30ms for each flow rate and not repeated. \( T^* \) is constant during the whole experiment and chosen as described in section 2.2.1. The PW is located inside a glass tube with an inner diameter of 3mm and the sensor pointing towards the center of the tube. This is placed in a water bath (Saco Spangenberg GmbH, Emmerich, Germany) at room temperature, which will be measured with the Hart Scientific Thermometer type 1502A (Hart Scientific, American Fork, Utah). The water flow will be made by a simple static pump. The reference flow was measured with the T110 lab tubing flow meter (Transonic Systems Inc., Ithaca, NY) which could be connected to the RAN. The RAN sends a feed at 100Hz to the computer where the data, \( V_T \) and reference flow, are recorded through the serial port by Labview, through this port also the feedback signal, \( V_{EX} \), is sent to the RAN. With this experiment the sensitivity of the sensor is investigated. The results of \( V^2_{EX} \) at different flow rates will be fitted to a power law and presented with the 95% confidence intervals.
Figure 2.8: Presentation of the CTA experiment. A PW (e) is placed in a glass tube (c) in a water bath (d) at a constant temperature (b, thermometer). A pump (a) forces water through the tube. The PW signal, obtained by the RAN (g), is transferred to the notebook (h) where a Labview based controller computes the new excitation voltage for the PW-RAN combination. The flow meter (f) supplies the verification flow.

Flow tracking

In this experiment the ability of the temperature signal controlled PW-RAN combination to track a unsteady periodic signal, here a sinusoid, is investigated. Due to the time delay caused by the computer it is not expected that a signal with a frequency above 2Hz can be tracked, therefore a sinusoid with ground frequency of $\frac{1}{2}$Hz is taken for the flow. The consistency of the CTA is investigated by adding a distortion in the flow signal, this is accomplished by briefly turning the flow off and on.
Chapter 3

Results

3.1 Pressure switch

In this experiment it is investigated if the pressure switch, see figure 3.1, should be turned on during CTA with the PW-RAN combination. The response of the temperature signal $V_T$ of a pseudo PW on a stepwise increase of the excitation voltage $V_{EX}$ was registered and analyzed.

Figure 3.1: The RAN Xpress tested with the pseudo PressureWire for the open (the nonlinear curve) and closed (the linear curve) configuration of the pressure side of the PW-RAN bridge by stepwise increase of $V_{EX}$. 
The data in figure 3.1 shows the $V_T-V_{EX}$ relation in the pseudo PW with an unexcited pressure branch. What can be seen is that the relation between $V_{EX}$ and $V_T$ is, contrary to the expectation of equation 2.5, not linear if the active side is switched off. When the active branch is excited the expected linear behavior, from equation 2.5, is observed. The non-linear behavior in the $V_T-V_{EX}$ relation with unexcited active branch could not be explained. Therefore it was chosen to excite both branches in all other experiments.

3.2 RAN verification

The constructed SAN is used to verify the results obtained from the RAN, both a PW-RAN and a PW-SAN combination were examined at increasing excitation voltage. Figure 3.2 shows the $V_T-V_{EX}$ relation of two PW’s on the PW-RAN and PW-SAN combination. The behavior of $V_T-V_{EX}$ in the PW-RAN combination is not monotonic, after 7V a steep increase of $V_T$ is observed in both PW’s. The behavior of the temperature signals from the PW’s in the PW-RAN combination differ, the first is non-monotonically increasing, the second is at first decreasing and then increasing. The plateau between 8V and 9V of the first PW is at saturation level of the ADC. Due to possible ADC saturation a different $T^*$ had to be chosen for the different PW’s, therefore it was not expected that the results would overlap but the behavior change is not understood.

In the PW-SAN combination the linear effect due to an imbalance of the bridge was eliminated, changes in $V_T$ can therefore directly be related to changes in $R_P$. For this setup also the behavior in water was examined and this is plotted in the same figure. It is observed, figure 3.2(b), that all three curves show a monotonically increasing decay of $V_T$ with an increase of $V_{EX}$. Comparing the results of the PW in water with those of the PW in air show that the temperature rise in water is less than that in air, which is expected due to the higher conductivity of water compared to air.
Chapter 3. Results

Figure 3.2: PW-RAN, PW-SAN comparison of air measurement. (a) A behavior change around 7V excitation is noticed. The non-monotonic behavior is questionable. (b) Monotonic behavior is observed.

3.3 Static calibration

With this experiment the fitness of the sensor for the CTA application is investigated in a temperature controlled water-bath. Prior to the fitting, the negative flow rates (near 0 mL/min) were made positive to make curve fitting possible on the power law model. If negative flow rates did exist then treating them as positive should not make a difference for the CTA method which is only effected by the absolute flow rate. The power law fit was made with MATLAB® curve fitting toolbox based on the trust-region methods for
Figure 3.3: The $V_{EX}^2$ flow rate relation (purple dots), a power law fit (straight blue curve), and a 95% confidence interval (dotted red curve)


\[ V_{EX}^2 = a + b \cdot Q^c \]  \hspace{1cm} (3.1)

with:

\[ a = -12.92, \hspace{1cm} ci(-13.05, -12.8) \]  \hspace{1cm} (3.2)
\[ b = -0.3443, \hspace{1cm} ci(-0.3601, -0.3286) \]  \hspace{1cm} (3.3)
\[ c = 50.27, \hspace{1cm} ci(50.04, 50.49) \]  \hspace{1cm} (3.4)

where \( ci \) stands for the 95% confidence interval bounds. The 95% confidence interval in figure 3.3 shows that the flow rates in the region of interest for coronary flow assessment cannot be distinguished from each other accurately.

3.4 Dynamic performance

3.4.1 No distortion

Figure 3.4 shows the flow and the controlling quantity $V_{EX}$ versus time. The unsteady flow does not resemble a sinusoid with period 2s but a signal with a ground frequency
Figure 3.4: CTA experiment with a PW-RAN combination for a pulsatile flow (solid line). The controller output $V_{EX}$ (dotted line) tracks the ground frequency of the flow signal with a phase lag of about 0.3s.

approximately $\frac{1}{2}$Hz and more higher frequencies. Although there is a phase lag of about 0.3s the ground frequency of the flow is tracked. The mean error of the controlled quantity, expressed in the analog to digital converter unit (ADU), is -0.3ADU, with the standard deviation of 81 and an absolute maximum of 146ADU. With respect to the mean, the controller is good, on average the controlling condition is satisfied but the standard deviation indicates that the controller should be optimized.

3.4.2 Distortion

The experiment discussed above is a subset of this experiment, the conditions are the same except for a distortion. After the experiment of which figure 3.4 represents a subset, the flow was suddenly turned off and on again. By this the controller was tested on its ability to handle a distortion. After the distortion the controller traced the signal as before but on a different level of $V_{EX}$, see figure 3.5.
Figure 3.5: CTA experiment with a PW-RAN combination for a pulsatile flow. After the data set shown in figure 3.4 the flow (solid line) was turned of and on again. The tracking of the signal is again obtained but now on a different level of $V_{EX}$ (dotted line).
Chapter 4
Discussion and Conclusion

This analysis investigated the fitness of the PW-RAN combination for CTA application. It was found that the internal update frequency of the RAN satisfied the demand for CTA, though the maximal power supply initially did not, and, therefore, had to be doubled. With an experiment it was found that both sides of the bridge had to be excited; with only the passive side excited the output signal could not be understood. This does not object to the method used by Geven and Van der Horst [5, 8], who excited only the passive side, since in their method the RAN was not used. The model that was available for the RAN was tested with the SAN, they did not show equal behavior which made computations of internal parameters of the RAN model impossible, like \( R_P \). Furthermore it was seen that in an experiment of two different PW’s the PW-RAN combination gave different behavior, where these PW’s gave similar results in the PW-SAN combination. It is suggested that the deviation between the RAN and the SAN are caused by the higher excitation voltage for which the RAN was not designed. During the static calibration procedure of the sensor a problem occurred when control was above 7V. A behavior change around 7V was also reported in the PW-RAN combination but not in the PW-SAN combination, see section 3.2, which suggests that this problem is inherent to the use of the RAN.

For the data analysis a relation between \( V_{EX}^2 \) and the flow rate was computed under the assumption that pressure does not effect the power dissipation. The pressure does however change the resistance of \( R_A \) and by that the energy generated in \( R_A \) will change as well. The effect of pressure changes during flow measurements and vice versa should be studied. For this CTA application the measure \( V_T \) was controlled though there was a dependence \( V_{EX} \) on \( V_T \) causing multiple solutions with respect to \( R_P \) and \( V_{EX} \) that satisfies the controlling condition \( V_T = \) an arbitrary constant. A different measure that is controlled constant has to be found for CTA on the PW-RAN combination to work. It should also be noted that the curve fitting on the data set was done with respect to the power law model dictated by the CTA theory and might be insufficient for this application.

The wide range of the confidence levels of the static calibration experiment showed a poor sensitivity of the sensor the flow changes. Besides the poor sensitivity of the sensor observed in the static experiment the dynamic experiments showed that the controlling
should be optimized in order to decrease the phase-lag, this can be done by investigating
the dynamics of the system.
From the dynamic experiment with distortion the effect of a non-specific controller was
observed. The control condition, $V_T$ corresponding to a certain setpoint, can be satisfied at
different values of $R_P$. There is no unambiguous relation between $V_T$ and the temperature
of the sensor. With a control based on $V_T$ the PW-RAN combination cannot function
as a constant temperature anemometer. This experiment shows the effect of the lack of
strictness of the controlling on $V_T$ described in the experiment with static flow.
For further research it is advised to control a parameter that is uniquely related to one
temperature. The author suggests the parameter $\frac{V_T}{V_{EX}}$ for future investigation to eliminate
the dependency of the excitation voltage ($V_{EX}$) on the control demand. The effect on pres-
sure difference should also be investigated with respect to CTA. Furthermore the effect of
the cable resistor on temperature should be taken into account, especially when conducting
a CTA measurement in a fluid above room temperature, e.g. blood at body temperature.
This study shows the possibilities and the limitation of the PW-RAN combination for the
CTA application. The author advises the construction of a pressure and flow measuring
system based on the PW-RAN combination, initially without the RAN but with the knowl-
edge of its possibilities. In that way this study can contribute in the use of the PW as an
anemometer and pressure sensor.
Acknowledgment

This internship was made possible by (and an excellent experience thanks to) Radi Medical Systems Uppsala, Sweden. I would like to thank the people at Radi for their interest in and help with my project and for the nice conversations.
Bibliography


[13] Radi Medical Systems, Uppsala, Sweden