Measurement of flow velocities of fluids by low-cost radar sensor HB100

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Abstract—**This thesis discusses an alternative way to determine the flow velocity of fluids. In contrast to conventional sensors, a measuring method is evaluated which is characterized by a comparatively ”large” measuring distance and is also able to measure through different materials of hoses and pipes. By emitting electromagnetic waves with the use of a CW radar, a frequency-side shift, also called Doppler shift, occurs by reflection at the moving fluid molecules. With the help of this Doppler effect, the flow velocity can be determined and calculated relatively easily. In addition, it is to be investigated whether the detection of the Doppler frequency is also feasible with a low-cost sensor. This sensor has the property that the parameters, for example with regard to the radiated power and transmission frequency, are not fine-tuned and adjusted, in contrast to sensors specially developed for this application. As a result, effects such as absorption and reflection of electromagnetic waves can occur, for example on the fluid surface, which should also be examined more closely.**

I. INTRODUCTION

Sensors are becoming increasingly important in today’s world with the progress of ”Industry 4.0”. For almost all problems there is a multitude of sensors based on the most different physical principles. Due to this fact, there is a separate sensor for each application. This limitation means that there are many sensors on the market, which are improving in their accuracy, but can only be used for very specific applications. Many measuring principles are suitable for a larger bandwidth for which they are actually intended.

Sensors that detect the flow velocity of fluids are also specially designed for this application area. However, these are limited by the composition of the respective fluid. Furthermore, for smooth detection, these sensors must be mounted directly in the system, i.e. the measuring device must be located in a pipe system. The liquid surrounds or flows through it. This is a problem for chemical companies, especially due to the use of corrosive and toxic chemicals.

For this reason, the question arises whether it is technically possible, as an alternative to conventional methods, to measure the flow velocity using non-contact sensors and thus become independent of fluid properties. One possibility to detect velocities without contact is the use of a CW radar. The Doppler shift, which occurs after reflection from moving objects, can be used to determine the velocity. However, today’s radar systems are mainly used in the aviation and shipping industry. It can be stated that in contrast to flowing fluids, larger dimensions in speed and distance play a role here.

In addition to testing the feasibility of such measurements with a CW radar, it is also investigated whether low-cost sensors with lower power from the Internet (e.g. HB100) provide the same results as sensors specially trimmed for this application.

In order to confirm or disprove the above mentioned hypotheses that e.g. the flow velocity of fluids can be measured by using Doppler shift, some questions have to be answered. For example, it is essential to check the degree to which fluids or the molecules they contain reflect the emitted electromagnetic radiation. If the degree of reflection is too low, the result is that the reflected power is no longer distinguishable from the noise signal of the electronic components and the surroundings/environment. Furthermore, it must be clarified to what extent the Doppler shift can be detected in the frequency domain. For example, at low flow velocities (a few cm/s), the Doppler frequency may theoretically be in the mHz range, which can no longer be detected by a spectrum analyzer. As a result, the reflected signal must be processed by an amplifier in such a way that, for example, a microcontroller can calculate the flow velocity by means of a Fast Fourier transformation and additional suppression of the noise power.

II. REFLECTION OF ELECTROMAGNETIC WAVES AT THE AIR-WATER INTERFACE

In order to get an overview of the level to which the emitted power is detected at the receiver of the radar sensor, it is essential to check the reflection on fluid surfaces of electromagnetic waves in the X-band range more precisely before putting the radar sensor into operation. In detail this means that it must be determined whether the molecules contained in the fluid transmit, absorb or reflect at a certain frequency range.

Water, for example, is highly transparent in the visible range of light and hardly reflects the radiated power. By knowing the transmission frequency of 10.525GHz [1], [2] and a resulting wavelength of

$$\lambda = \frac{c}{f} = 28,5mm \tag{1}$$

the relection coefficients R with an assumed refractive index n = 1.33 (this refractive index originally applies only to the visible spectrum, but is neglected due to the estimation that is made) can be determined for certain wavelengths [3]:

- for $\lambda_1 = 10mm$:

$$R_1 = \frac{((n-1)^2 + (n*k_1)^2)}{(n+1)^2 + (n*k_1)^2} = 0,738 \tag{2}$$

- for $\lambda_2 = 50mm$:

$$R_2 = 0,428 \tag{3}$$

As a result of the calculated reflection coefficients it can be concluded that the reflected intensity, which is detected at the radar sensor, is quite high enough to determine the Doppler frequency and the associated flow velocity. However, transmission is not taken into account in this calculation. Therefore a lower degree of reflection is to be expected.

In addition, the radar cross section or effective back radiation area σ also plays an important role in estimating whether a sufficiently high power is reflected at the air-medium fluid interface. This factor reflects to a certain extent the degree to which the transmitted power is scattered at the surface of the target (in this case the molecular compounds contained in the fluid), so that a statement about the reflection can be made when this area is identified. If this area becomes too small, the resulting received power decreases [4], [5]:

$$P_{Receiver} = \frac{P_{Transmitter} * G^2 * \lambda^2 * \sigma}{(4*\pi)^3 * R^4} \tag{4}$$

Because this value is difficult to specify for both water and other fluids, the final reflection can only be estimated very unprecisely in connection with the above calculation.

III. ELECTRONIC ANALYSIS OF THE FLOW VELOCITY

The estimation carried out in Chapter II shows that the amplitude of the reflected carrier frequency modulated by the Doppler frequency ($f_c \pm f_{Doppler}$) is at most in the range of nV to µV. Because noise power is added to this signal, the original output signal of the radar sensor for a FFT analysis is lost in noise. This makes the use of amplifier electronics even more important. On the one hand, this is supposed to suppress as much noise power as possible and, on the other hand, to amplify the Doppler shift, which is generated at the output of the sensor after mixing the transmitted and received signal, so that an analysis e.g. by using a microcontroller is possible.

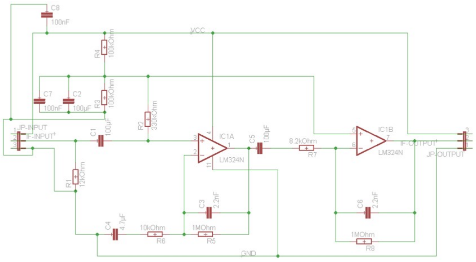

Fig. 1. Block diagram of the amplifier

A. Processing of the echo signal by operational amplifier

A possibility to amplify the received signal so that it can be evaluated is to use a dual amplifier circuit with an operational amplifier and band-pass filters (s. Fig. 1). By modifying the cut-off frequencies of the high & low pass filters, it is possible to change the bandwidth in such a way that the sum frequencies generated by the mixer are filtered and noise power is reduced. In order to tune the filters correctly, it is necessary to clarify in which frequency range the Doppler frequency can be expected. At a flow velocity of a few cm/s, the Doppler shift can be determined using equation 5 [6].

$$f_{Doppler} = \frac{2 * v_{flow} * \cos\Theta}{\lambda} \leq 1Hz \tag{5}$$

In addition, the sensor should cover a wide dynamic range with regard to the flow velocity. Based on these findings and requirements, the filters can be dimensioned. To investigate the frequency-dependent gain and the influence of the filters in more detail, this circuit is simulated with LTspice XVII (s. Fig. 2).

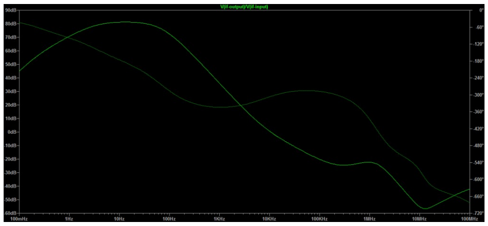

Fig. 2. Simulation of the frequency-dependent amplification of the amplifier

As a result of the above mentioned modifications, an amplification at 10Hz of approx. 80dB can be achieved. At a frequency of 0.6Hz the gain is still 50-60dB. With the help of this gain even microcontrollers are able to detect the output signal after amplification. However, it must be noted that the bandwidth is relatively wide. This means that the noise in connection with the high amplification plays an important role. To get an overview of the orders of magnitude of the noise, the occurring noise power is also simulated (see Fig. 3).

The results of the simulation show that the gain is high enough to process the received signal with the use of a microcontroller, but the noise power increases depending on the bandwidth to such an extent that it can no longer be neglected. To reduce this influence on the measured values,

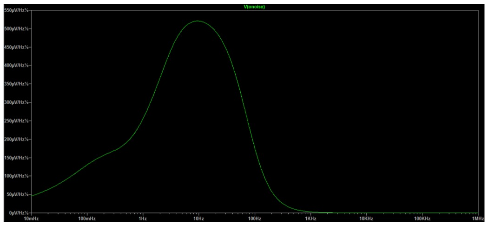

Fig. 3. Simulation of the amplifier noise power

the number of measurements N can be increased. By forming the average value, the noise is averaged out by the factor $\sqrt{N}$.

B. Analysis of the measurement signal with a microcontroller

For this analysis, a microcontroller, especially an Arduino Uno due to the AVR chip, can be used for frequency analysis. Compared to other manufacturers, this has the advantage that a large number of libraries are available for a wide range of applications. The library "FreqPeriod Library" is able to detect and determine the frequency at pin 7 of the Arduino. The functionality of the library is similar to a Schmitt-Trigger.

To calculate the frequency, a counter (TCNT1) runs in the background, which is incremented step by step with a 16MHz clock. As soon as the signal has a zero crossing at the internal Arduino comparator, the current state of the counter is written into the capture register ICR1. At the next zero crossing the difference between the current counter value and the capture register is formed. This time difference corresponds to the signal period and can be converted into a frequency [7].

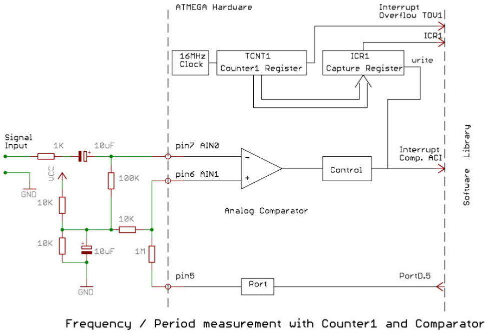

Fig. 4. Schematic overview of the functionality of the Arduino library [7]

This program records 300 measured values with a measuring interval of 300ms, whereby these settings can be changed in the program. When all measurements have been taken, the program stops automatically and displays both mean value and standard deviation using Arduino's own statistics library. The calculated values are transmitted via the serial interface to a computer, which visualizes the data with the help of a terminal/serial monitor.

IV. DATA LOGGING

A. Construction of the measurement setup

In addition to the design of an electronic solution for the evaluation, the correct construction of a measurement system is essential. Among other things, it has to be ensured that an evaluation can be made if the measurement of the flow velocity of fluids is possible at all. Furthermore, it should be investigated to what extent it is practicable to measure through materials. Based on these requirements, a modular and adjustable measurement setup with an open and closed measuring channel with variable hose diameters (s. chapter IV-C) can be developed (see Fig. 5).

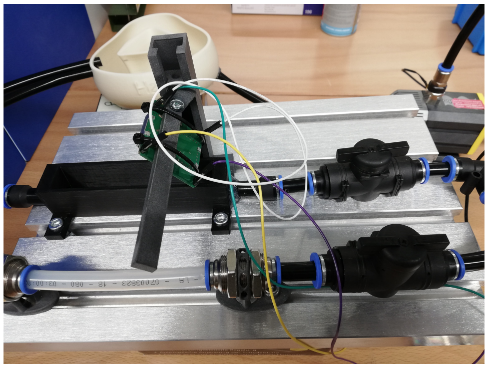

Fig. 5. Overview of the measurement setup

With these two measurement options, measurements can be performed at maximum receiving power without material-related losses and the transmission of electromagnetic waves through materials can be tested.

This adjustable measurement setup is required to obtain reliable and reproducible measurement results. For example, the distance between sensor and fluid must be minimal for the highest possible receiving power (s. Eq. 4). Furthermore, it is advantageous if the angle between antenna and fluid surface is kept as small as possible, so that an optimal analysis of the Doppler frequency with regard to height is guaranteed. Especially the last point has to be considered, because due to the high dynamic range of the possible flow velocities (s. III-A) also relatively small Doppler frequencies can occur (s. Eq. 5).

B. Measurement against a stationary object for interference determination

So far, noise has only been examined and analyzed in detail in the simulation of the used amplifier (see chapter III-A) and in the estimation of the reflection of electromagnetic waves (see chapter II). However, in order to better assess the overall noise behavior with all components (e.g. receiver, cable connections and environmental influences), a theoretical consideration is no longer sufficient.

The noise behaviour can be determined by measuring against a non-moving surface. In the ideal case, the sensor does not

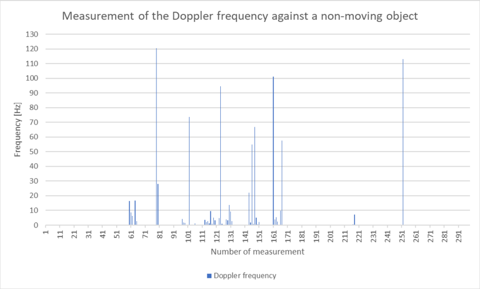

Fig. 6. Measurment of the Doppler frequency against a stationary object (e.g. wall)

deliver Doppler frequencies. In this measurement (s. Fig. 6) it can be seen that there are peaks regarding a measured Doppler frequency. Some of these peaks are due to movements behind the sensor caused by the radiation pattern (s. Fig. 7) of the patch antennas.

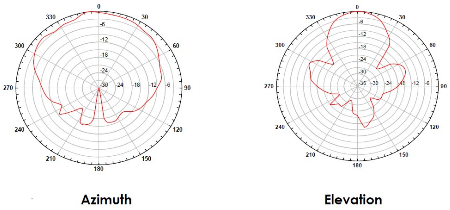

Fig. 7. Antenna diagram of the patch antenna of the HB100 [1]

Thus the antennas have an area of illumination behind the sensor in addition to the main and side lobes in the measurement direction. Therefore it must be ensured during further measurements that there is no movement in the surrounding of the sensor.
Furthermore, it can be observed that the peaks that are not caused by movement are triggered by noise power, among other things. Thus, this factor of ”disturbance” of the measurement signal is not insignificant and must be taken into special consideration in later measurements.

C. Measurement of flow velocity in a hose section

After analyzing how noise and other environmental parameters influence the Doppler frequency measurement, the flow velocity can be determined with the help of the constructed measurement setup. In addition, different flow rates can be realized with the help of a software-supported pump and the fluid temperature can be recorded at the same time.

Parameters of measurement:

- Tube diameter = (10x8)mm
- Rotation speed of the pump = 3000rpm
- Flow velocity at the flow meter = 69l/h
- Water temperature = 22.9°C
- Measuring angle of the sensor = 45°

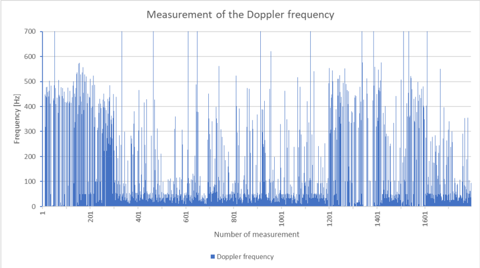

Fig. 8. Measurement of the Doppler frequency at the closed measuring channel

As already shown in Fig. 8, the approx. 1800 measured values fluctuate very strongly and a tendency cannot be read off. For this reason, the arithmetic mean value is $\bar{f}_{Doppler} = 343,85Hz$ and the corresponding standard deviation $s = 4263,59$. Already from this standard deviation it can be seen that no reliable statement about the flow velocity can be taken. In theory, the Doppler frequency mentioned above would result in a volume flow of 1254.02l/h. In comparison to the flow sensor's data of 69l/h the calculated value does not correspond by far and therefore a statement about the flow velocity determined with a CW-radar is not possible. An explanation for this significant difference in the values will most likely be the influence of noise, so that the actual Doppler frequencies are covered in terms of level. Furthermore, the influence of air bubbles in the liquid, for example, cannot be neglected. These additionally falsify the measurement signal by scattering the electromagnetic waves and by different speeds due to interaction with the tube walls.

V. CONCLUSION

Based on the above results, it can be concluded that CW radar sensors that are not specifically designed for this application are only suitable to a limited extent for measuring the flow velocity. For example, due to the antenna characteristics, the influence of the measurement environment is very important, as movements behind the sensor can be detected which influence the original measurement signal. However, this effect can be eliminated by suitable shielding around the measurement setup so that external influences cannot influence the measurement process.
In summary, it can be concluded that, if improvements such as optimized signal evaluation and noise suppression are implemented, it is quite possible to measure the flow velocity. However, it cannot be predicted today whether this method will be able to replace conventional measuring methods in the future in terms of efficiency and accuracy.

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