An affordable Airborne Ultrasonic Sensor for Predictive Maintenance Applications

José Ramón Blanco
TWave S.L.
Llanera, Spain

Juan Menéndez
TWave S.L.
Llanera, Spain

Francisco Javier Ferrero
Department of Electrical Engineering
University of Oviedo
Gijón, Spain

Alberto López
Department of Electrical Engineering
University of Oviedo
Gijón, Spain

José Ramón Villar
Department of Computer Science
University of Oviedo
Oviedo, Spain

***Abstract*—The capture of ultrasound is a technique that is currently provoking an increasing interest among theorists and specialists in predictive maintenance, as it allows the detection of failures that can go unnoticed if other techniques only are used. This work is devoted to the development of an affordable airborne ultrasound sensor for the detection of natural ultrasound emissions, such as those caused by the friction of moving parts of machines, small gas leaks or cavitations, electrical faults, etc. The sensor is oriented to detect faults in machines and designed for permanent installation in industrial environments. It is specially designed to be used in conjunction with a data acquisition device which permits data to be collected for equipment without the presence of an operator and to obtain detailed information about the type of failure.**

Keywords—bearing condition, electrical inspection, leak detection, predictive maintenance, ultrasonic.

I. INTRODUCTION

Besides infrasound and audible sound, ultrasound refers to any sound pressure wave with a repetition frequency greater than 20 kHz. The characteristics of ultrasound, especially around 40 kHz are particularly interesting for inspectors listening for symptoms of aspects of failure.

The characteristics of the ultrasonic phenomena make the use of ultrasonic sensors possible in a huge number of industrial applications related to predictive maintenance, such as pressure leak detection, monitoring of bearing condition, electrical discharge detection, liquid flow monitoring, tightness testing [1-2].

Ultrasonic analysis is one of the less complex and less expensive predictive maintenance technologies; the equipment is relatively small, light, and easy to use. The cost of the equipment is moderate, and the amount of training is minimal when compared to other predictive maintenance technologies.

There is a growing variety of sensors and instruments currently available on the market to detect these natural sources of ultrasound. There are analog and digital devices, some with basic functions and others with powerful features including frequency tuning, on-board data logging and on-board sound recording [3]. Analog ultrasound instruments provide quick, simplified testing for basic trouble shooting and leak inspections. On the other hand, ultrasound instruments can be installed at a fixed point of special interest [3] or to be portable [4-5]. Permanent instruments are usually simpler systems that require an external instrument to capture and digitize the data. Portable instruments are autonomous instruments that digitize the collected signal and have a display or indicator to show the detected value.

This work proposes an affordable analog ultrasonic device for permanent use is proposed. Unlike conventional ultrasonic sensors it had to have high sensitivity and a dynamic output voltage that enabled the direct reading and analysis of the signal in the frequency range of ultrasounds.

This type of device does not seek to give a quantitative but rather a qualitative indication of the signal level. The aim is to detect small variations in the emission of ultrasounds. It is specially designed to be used in conjunction with a data acquisition (DAQ) device [6]. In combination with a DAQ device it can be a powerful tool for permanent monitoring because it is possible to install several sensors on the installation collecting data for industrial facilities without the presence of an operator. In this operation mode detailed information about the type of fail can be obtained. This could be an important advantage against other more expensive technologies, like vibration analysis.

Unfortunately, there are no recent publications related to the proposed work. On the contrary, airborne ultrasound sensors have been developed for specific applications, such as monitoring dental implants [7], liquid-level inspection in bottles [8], distance measurement [9], muscle state [10], transmission tomography in gaseous media [11] or even for the detection of brick joints behind a wall painting [12].

The rest of this work is organized as follows: The materials and methods that include the design of the sensor are described in Section II. The airborne ultrasonic sensor is evaluated in Section III. Conclusions are presented in Section IV.

II. MATERIALS AND METHODS

Fig. 1 shows the block diagram of the proposed ultrasonic sensor. It consists of an input signal conditioning to amplify the ultrasound captured by the ultrasonic transducer, and to filter it in the desired frequency range, eliminating components of other frequencies that disturb the detection of the ultrasonic signal. The gain control stage enables the gain of the amplifier to be adjusted according to predetermined values. Finally, the output signal conditioning allows both a dynamic output voltage, between ±5V and another static output current, I_O, proportional to the RMS value of the ultrasounds in the range of 0-20mA. The external power supply is +24V.

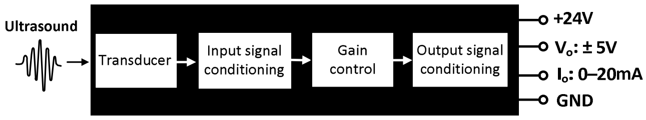


Fig. 1. Block diagram of the ultrasonic sensor.

The ultrasonic receiver is the model 400ER250 made by Pro-Wave Electronics Corporation. Table 1 shows the main specifications related to the design of the sensor [13]. A load resistor of 39 kΩ is connected in parallel to the receiver to avoid the influence of outside noise.

From Fig. 2 we can find the corresponding sensitivity, that is -52dB. The equivalent sensitivity expressed in mV/Pa can be obtained by the expression 20log (S/S_0), where S is the sensor voltage (V) and S_0 is the reference sound pressure (10V/Pa). The equivalent sensitivity is 250 mV/Pa and an amplification stage will be necessary.

TABLE I. SPECIFICATIONS OF THE ULTRASONIC RECEIVER

Specification	***Value***
Centre Frequency	40.0±1.0 kHz
Bandwidth (-6dB)	1.0 kHz
Transmitting Sound Pressure Level at 40.0 kHz; 0dBre 0.0002 mbar per 10 Vrms at 30 cm	115 dB min.
Receiving Sensitivity at 40.0 kHz at 40.0 kHz 0dB = 1 volt/mbar	-70 dBmin.
Capacitance at 1 kHz ±20%	2400 pF
Max. Driving Voltage	20 Vrms
Total Beam Angle -6dB	30º typical

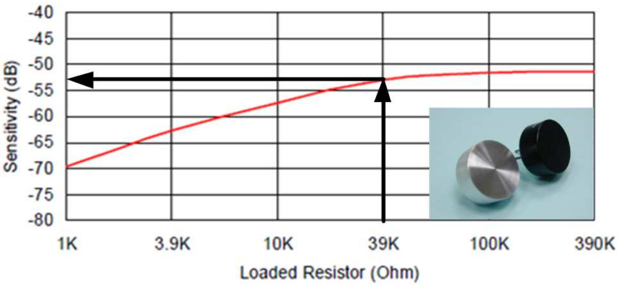


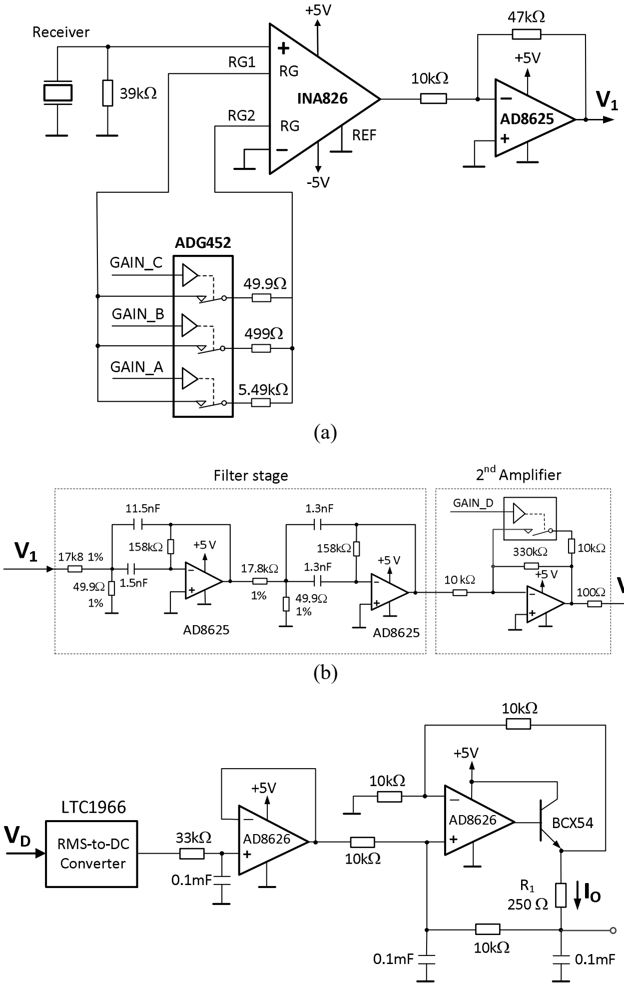
Fig. 2. Sensitivity variation vs. loaded resistor of the receiver.

The receiver is followed by a stage amplifier as shown in Fig. 3a the main component of this stage is an instrumentation amplifier (IA). The gain of the IA is established by means of a resistor connected between the terminals RG1 and RG2. The value of this resistor is selected by an analog switch (ADG452) whose digital inputs are set by a microcontroller. Thus, it is possible to multiply the input signal by 1 (without resistor), 10, 100 or 1000. The amplification circuit is completed by a 4.7 V/V gain inverter amplifier made from the operational amplifier (OA). The main parameters to consider when selecting the IA and the OA are the gain bandwidth product and the slew rate.

The filtering stage consists of a fourth order multiple feedback band-pass topology. This topology is very interesting in this application as it presents a strong rejection in the suppressed band and a greater tolerance to the values of the components for the frequency adjustment [14]. The described amplification and filtering stage are completed with a final post-amplification stage with a gain of 33V/V. The objective is to have a dynamic ultrasonic output signal, accessible by external data acquisition equipment and in the range of ±5V. Fig. 3b shows the electrical schematic of the circuit to obtain the dynamic output. To convert the dynamic signal into a slower and easier to read signal by conventional acquisition systems, a stage is added that extracts the RMS value from the dynamic signal and gives a value proportional to it between 0 and +5V. This stage is based on the LTC1966 Linear Technology RMS-to-DC converter. It is also usual to want to have an output current. For this purpose, the circuit of Fig. 3c is used. It is a voltage to current converter in the range 0-20mA, where 20mA corresponds to +5V RMS. The output current, I_o, is approximately equal to V_{RMS} divided by R_1.

A low-cost microcontroller is used to control the gain of the sensor. It was selected the Microchip PIC12F675 due to its small size, requiring no external oscillator and the availability of analog inputs.

For the gain selection a system based on load resistances was chosen. The gain is automatically adjusted according to the resistance between one of the terminals of the external connector and the mass. A microcontroller device (not shown) is used for measuring this resistance through one of its analog inputs and applying the corresponding gain, selecting the gain from a total of 5 possible values as shown in Table II. Fig. 5 shows three typical waveforms at the output of the sensor, where V_D represents the dynamic output voltage and V_S the static one.

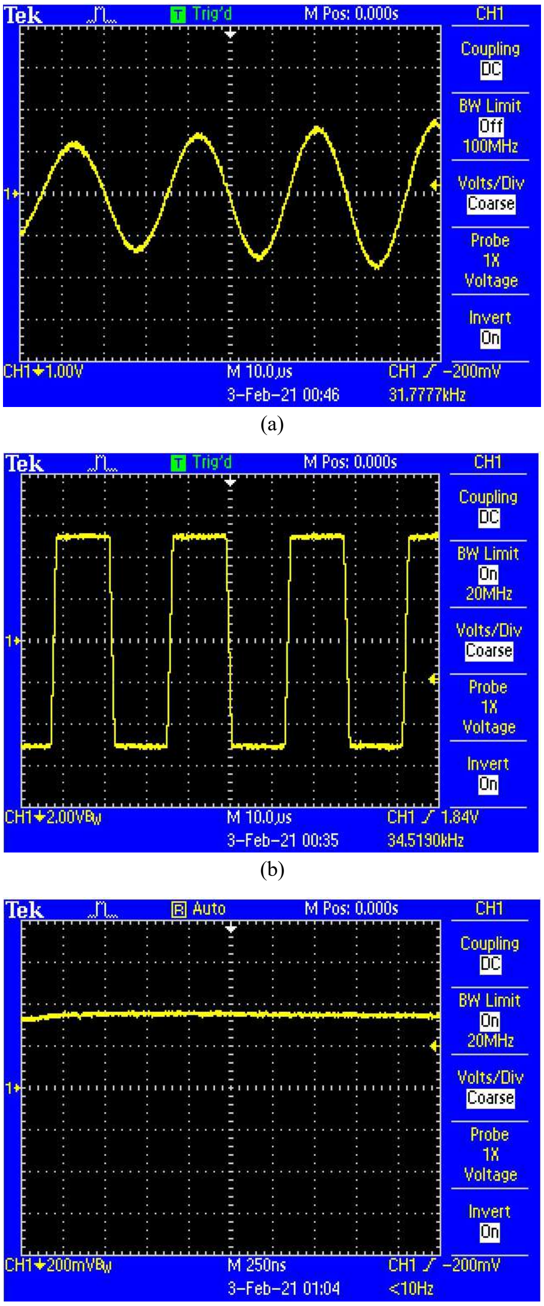


(a)

(b)

(c)

Fig. 3. Electrical schematics of the a) input signal conditioning; b) and c) output signal conditioning.



(a)

(b)

(c)

Fig. 4. Typical waveforms recorded using a pipette to generate ultrasounds: (a) and (b) Dynamic outputs; (c) Static output.

TABLE II. SELECTION OF AMPLIFICATION

Range #	***Resistance Selection***	***Amplification (dB)***	***Signal Range (dB)***
1	Short Circuit	0	< 90
2	10 kΩ	30	< 60
3	33 kΩ	50	< 45
4	100 kΩ	70	< 35
5	Open	90	< 25

If the lecture of the input analog level is above the range, then the range of the gain must be increased. By contrast, if the lecture of the input analog level is below the range then the range of the gain must be decreased. Gain change values are calculated with hysteresis to avoid unwanted fortuitous changes.

Fig. 5. General view of the ultrasound device developed.

Fig. 5 shows a view of the ultrasound device. The main body is a stainless-steel cylinder of 32 mm in diameter, which is provided with an external thread (M30) to facilitate its assembly. The device is designed for outdoor conditions and with sensitivity suitable for the application.

III. EXPERIMENTAL RESULTS AND DISCUSSION

To verify the correct functioning of the device, the ultrasonic detector for predictive maintenance SDT270 was used as reference meter [4]. It is high cost equipment that allowed the comparison of the results obtained with the developed sensor and the verification of their validity. In order to simulate the ultrasonic sources of an industrial plant, specific ultrasonic emitters connected to a wave generator to modulate their power were used, as well as everyday objects that could simulate signals of very low power, i.e. empty plastic bottles, pipettes, etc. In this way Fig. 6 shows the calibration curve of the sensor as a function of the acoustic, using the reference meter to obtain the sound values. The dB measured by the sensor are calculated from the dynamic output voltage and the gain, according to the expression:

$$\text{Dynamic output (dB)} = 20\log(V_{D\,\text{rms}}/\text{Gain})$$

The ultrasonic sensor was tested both in the laboratory as well as in industrial environments. Five devices were assembled for this purpose. Table III shows the results obtained with from three prototypes, in relationship with the records provided by the reference ultrasound detector (SDT 270). As can be seen, the results have good repeatability and good linearity, which proves the ability of the sensor to become a commercial product.

It is important to note that this type of sensor does not seek to give a quantitative but rather a qualitative indication of the signal level. The intention is to be able to detect small variations in the emission of ultrasounds, the specific value in dB of the acoustic waves is not relevant, since it can vary a lot depending on the application.

It was verified that the response of the sensor maintains a high linearity in the logarithmic scale with respect to the applied excitation, even in several scales of gain. Using a pipette as a simulation of a small air leak, and the values read by the reference meter, the ability of the sensor to detect signals in the environment up to -100dB could be checked.

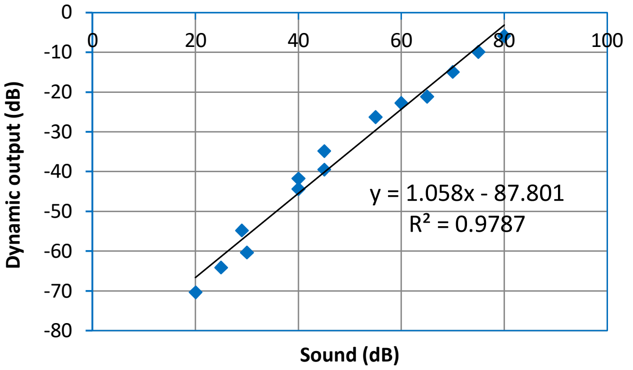


Fig. 6. Calibration curve of the ultrasonic sensor and general performance test results of the ultrasound sensor.

TABLE III. RECORDED MEASUREMENTS OF THREE PROTOTYPES AND THE REFERENCE DETECTOR AT DIFFERENT EXCITATION

Prototipe	*Excitation @ 39.5 kHz (mV rms)*	*Reference Detector (dBµV)*	*Static output (mA)*	*Dynamic output (mV)*
1	0	-3	0.50	70
	10	19	1.22	190
	80	37	9.20	1300
2	0	-3	0.65	95
	10	19	1.80	250
	80	37	11.4	1650
3	0	-3	0.60	85
	10	19	1.68	240
	80	37	11	1500

One of the most common maintenance applications for airborne ultrasound that can be applied at the plant is for condition monitoring [15, 16]. The sensor can be used to alert changes in condition and do a preliminary diagnosis. Operators must answer two questions: how to set the baseline and to decide if the recorded ultrasound is good or bad. Regarding the first question two methods are common: the comparison method and the historical method. The first one is a quick method in which the operator compares the readings at the same points on identical machines. The baseline can be established as the average value of the ultrasound levels at the compared points.

A preferred method for establishing baselines is the historical method. Using this method, the operator first establishes a route or database in the ultrasound software, which is subsequently loaded into the DAQ. Data is then collected at the various points along the route. Once the baseline has been set, if the readings are remaining consistent, the frequency at which the readings are collected can be adjusted. Once a baseline has been established through either the comparison method or the historical method, alarm levels can be set.

With respect to the second question, concerning how to know if the recorded ultrasound is good or bad, ultrasound imaging is the preferred method. It consists in recording the data of the ultrasound sensor and graphing it by means of spectrum analysis software. In this way the user can obtain an "image" of the sound that is being heard to analyze, diagnose, and confirm fault conditions in equipment. This method has the advantage of minimizing the error due to the subjectivity of the operator in detecting sound.

To illustrate these concepts with an example the airborne sensor was connected to a DAQ for condition monitoring of a 40HP motor powering a pump. When collecting the initial data for setting the baselines, the readings may need to be taken once per week for 4-5 weeks. Once the baseline is set, the readings can be taken once per month. Fig. 7 graphs ultrasonic data recording with the DAQ from the drive-end bearing. Collecting information is quick and inexpensive. Much more data can be taken extending condition monitoring to more machines which may have been overlooked by vibration due to time and costs.

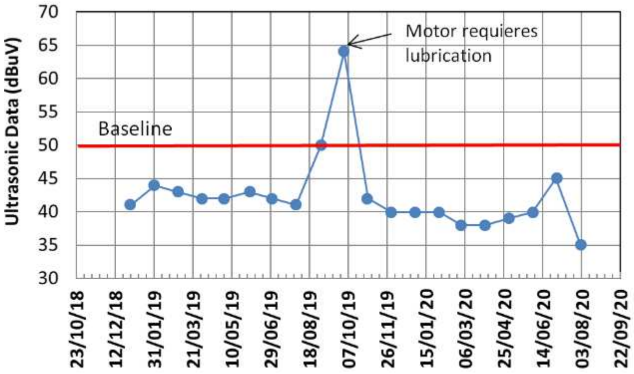


Fig. 7. Ultrasonic data from the drive-end bearing on a 40HP electric motor.

IV. CONCLUSION

This work describes the development of an affordable analog ultrasonic sensor especially suitable for use in predictive maintenance programs. This sensor has been designed to be used permanently connected to a data acquisition device. With the use of high performance and low-cost analogue components, it was possible to develop a very low-cost sensor capable of replacing very expensive consolidated technologies present in many applications today. Compared to the reference meter used in the tests, the developed ultrasonic sensor would be more than one order of magnitude lower in price. Most devices in the market for predictive maintenance are designed to be used as portable instruments. A permanent sensor permits collecting data to be collected for equipment without the presence of an operator, being an important feature.

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