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Evaluation of 77 GHz Radar for Industrial Fan Quality Inspection

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***Abstract*—Quality inspection is crucial in production lines. During the fabrication process, defects and imperfections can be present and the affected manufactured parts must be discarded. Such process must be fast and reliable to not slow down the production line and assure that out of tolerance parts are always identified. Different methodologies are investigated and applied to perform the task, but for companies, it is always of interest to discover novel methods to improve the quality inspection process. In this work, the manufactured under test is an industrial fan, and the test methodology proposed leverages a radar sensor. Two main quantities are extracted: the fan's rotation speed and its vibration displacement. To validate the radar method, reference sensors are used. At the end, a comparison in measuring rotation speed and vibration displacement with the radar and the reference sensors is provided.**

***Index Terms*—industrial fan, radar, vibration, measurement, quality**

I. INTRODUCTION

In production lines, quality inspection of the manufactured items is a fundamental step in discarding products affected by defects or not compliant with expected tolerances. An automatic in-line quality inspection system for industrial fans should fulfil the following requirements: good repeatability, reliability, flexibility, adaptability to different types of manufactured items and defects, and the capacity of being integrated in the production line [1]. Developing methods that fulfill such requirements is always of interest. In this work, attention is paid to the validation of industrial fans during the inspection procedure, and, in general, such a task can be performed by extracting quantities with direct or indirect methods leveraging vibration measurement. The latter can exploit two different families of sensors: contact and contactless ones. The former class commonly exploits accelerometers as they can be cheap and fast in providing the requested quantity for quality evaluation. From accelerometer measurements, anomalies and defects can be extracted, and the affected product can be discarded [2]. Accelerometers can be directly applied on the device under test or on a specific part of the test bench where the device is allocated during the inspection. Both methods can be tricky: sticking the sensor on the device implies a time delay needed to carry out the measurement and an operator to perform the check; using an accelerometer on the device supporting bench can collect corrupted measurements as the sensor is not directly applied onto the device [3], [4]. The main weaknesses with contact sensors can be overcome by using contactless methods. The gold standard for this latter measurement family is laser Doppler velocimetry [5]. The performance of such method are well suited for the quality inspection process and present advantages in comparison with contact sensing, like good repeatability, reliability, flexibility, and adaptability to different types of defects [1]. However, laser Doppler instrumentation is typically expensive and bulky, reducing the capacity to be integrated into the production line. Laser vibrometers are generally composed of a head containing the optical and electronic components (laser, photodetector, etc...), and an acquisition system used also to process the signals [6]. Albeit the efforts to design integrated laser vibrometers [7], only the most traditional versions are available in the market, and these are difficult to integrate into a quality inspection line. Another contactless inspection method can leverage acoustics measurements [8], [9]. Despite the simple installation and promising performance, microphones need a suited environment to provide reliable information. In a noisy environment, such as a production line usually is, the highly sensitive acoustic method can be frail and the risk of accepting out of tolerance products becomes non negligible.

As contactless approaches are always preferred by companies due to their low interaction with the device under test and minimal interference with the production line, the research of alternative contactless methods that resolve the aforementioned limits can move towards less conventional technologies.
For example, despite being designed and developed for

the automotive market, 77 GHz radar sensors can be used for vibration measurements [10]. In comparison to other technologies, these sensors are relatively cheap, robust against dirt and acoustic noise, and can be employed in harsh environments. The automotive radar form factor is suitable for integration within the production line, and this strengthens the idea of involving this technology inside quality inspection lines. To be considered as an option, the integration of an automotive radar in testing rigs must be carefully studied to verify if it fulfills all the industrial requirements needed in the specific case. As the output of these sensors is digital, they lend themselves well to the application of algorithms that make the validation process of components under inspection automatic. The radar method validation for this target application is the main task of this work.

In this paper, a preliminary study on the usage of mmWave radar sensors for industrial fan quality inspection is proposed, focusing on the analysis of the attainable performance. To carry out such analysis, a specific test bench is set up where reference sensors are arranged to obtain a performance benchmark. The paper is organized as follows: Section II introduces the methodology, the setup, and the radar used, Section III discusses the performed tests and the obtained results, and finally Section IV concludes the paper.

II. METHODOLOGY

In this section, the equipment used and the measurement setup are described. A brief discussion of the radar processing technique applied to obtain displacement measurements is also provided.

A. *Measurement setup*

In this work, two main quantities are used to perform the quality inspection: vibration displacement and fan rotational speed. Both can be obtained from an acceleration measurement, as the vibration is strictly related to the rotation speed of the fan. Measuring the rotation speed with an accelerometer is an indirect method and can be used, but as the focus is on the radar measurements, a laser tachometer is preferred. The reason is that the fan can rotate at a defined rated speed, which, however, also depends on how the component is installed on the test bench setup. Therefore, a reference sensor from which the rotation speed can be derived directly is preferred. The tachometer signal is acquired to measure the Revolutions Per Minute (RPM) of the fan and used as a reference value. The model used is a PCB ICP Laser Tachometer [11] which features a maximum of 100 000 RPM measurable. The measurable vibration quantity by the radar is the displacement and, for this quantity, the reference sensor will be an accelerometer. The one used is the PCB 356A32 [12]. Either the reference sensors used are acquired by the same acquisition system: the Dewesoft Krypton [13] properly configured to synchronously acquire the measurement signals at the same sampling rate. The arranged setup is composed of the fan under test, a support structure where the fan is anchored, and reference measurement sensors. In Fig. 1, the setup is schematized. The distance between the fan and the radar is indicated with d_0 and, in the setup used, is of $0.32\,\mathrm{m}$.

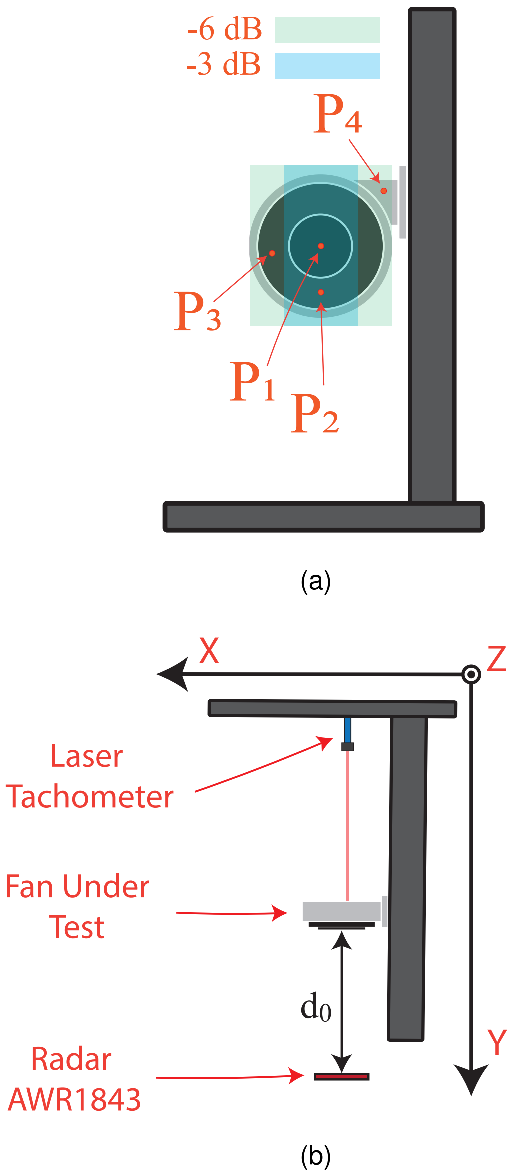

Fig. 1. Schematization of the used setup: a) front view where the orange dots are the accelerometer installation positions; b) top view with the laser tachometer and radar installation positions. The radar is placed at a distance d_0 from the fan.

As the radar has a raw field of view of 120°, multiple measurement vibration points are defined. The reason is that the radar will measure a mean displacement value derived from the different vibration amplitudes of all detected fan components. The positions are chosen considering the ISO 14695:2003 [14] standard. These positions are referred to as P_1, P_2, and P_3.

The laser tachometer is positioned on the opposite side of the fan with respect to the radar, as illustrated in Fig. 1b. To obtain the RPM measurement this sensor needs to point figures/tachometer.eps

(a)

figures_paper/disp_signals.eps

(b)

Fig. 2. Reference sensors signals: a) Laser tachometer, the upper graph is the RPM value derivation, and the lower graph is the temporal analog signal; b) displacement signals obtained from the defined reference positions.

to a reflecting rotating part of the fan. The pointed side has an exposed rotor that can be leveraged to perform the measurement, by sticking a reflective tape on it. The laser tachometer output signal will change its value when the laser passes over the reflective patch.

The Dewesoft Krypton is configured to acquire both the analog output of the accelerometer and the tachometer, with a sampling frequency of $20\,\mathrm{kHz}$. The used accelerometer provides values along the three reference axes but only the one along the Y axis is acquired. The reason is that the radar method can measure vibrations along its radial direction and, due to the setup arrangement, the same corresponds to the accelerometer Y axis. To convert the acceleration measures in displacement, a double integration and a high pass filtering are applied. The pass frequency of the filter is $5\,\mathrm{Hz}$. An example of the tachometer and displacement signals obtained from the used reference sensors is reported in Fig. 2. The process applied to these signals to obtain the measurement values is described in Section III.

TABLE I

RADAR CONFIGURATION PARAMETERS.

Parameter	Value
N_{ADC}	1024
f_s	12 MHz
S	42.003 MHz/µs
t_c	57 µs
B	3864.3 MHz
Pulse Repetition Time (PRT)	333 µs

B. Radar system and vibration measurement technique

The radar sensor used is the commercially available Texas Instruments AWR1843 BOOST board, a Frequency Modulated Continuos Wave (FMCW) radar. It features Multiple Input Multiple Output (MIMO) antennas and is configured to work in the frequency range $77\,\mathrm{GHz}$ to $81\,\mathrm{GHz}$, which is the short-range application for the automotive radar sensors. The MIMO implementation provides a virtual array composed of azimuth and elevation components. The beamwidth of the antenna design can be determined from the radiation patterns. At $3\,\mathrm{dB}$ drop in the gain, as compared to bore sight, the horizontal $3\,\mathrm{dB}$-beamwidth is $\pm 28^\circ$, and the elevation $3\,\mathrm{dB}$-beamwidth is $\pm 14^\circ$ [15]. Due to the vibration measurement technique, the radar configuration exploits only one transmitter and all four receivers. The reason is that the Time Division Multiplexing (TDM) operating mode can affect the vibration signal sampling. The technique used to extract the vibration measurement is described in [16] where a multi-chip radar sensor is employed. In [10], the same method is used employing a single chip radar. In both cases, the measurement error is in the order of a tenth of a micron. It is also demonstrated that the error is dependent on the distance of the target. In this case, the distance d_0 between the radar and the fan is less than a meter so an error of less than $10\,\mathrm{\mu m}$ is expected. The displacement measurement method is grounded on two fundamental points: the phase of the radar beat signal, indicated with Ψ_b, is modulated by the vibration of the target, and the displacement measure can be derived with the computation of the Discrete Fourier Transform (DFT) [17]. Computing the DFT of Ψ_b provides the displacement measure as demonstrated in [16]. The radar configuration must be chosen according to the radar detection and vibration measure requirements. The configuration is then chosen according to all the constraints and is reported in Tab. I.

The description of the configuration parameters follows: N_{ADC} is the number of samples collected for each beat signal and f_s is the beat signal sampling frequency; S is the slope of the transmitted chirp; t_c the chirp time duration, B the bandwidth and PRT the pulse repetition time. The latter parameter is the sampling time of the displacement measured by the radar. The maximum detectable vibration frequency is then $1.5\,\mathrm{kHz}$. This value is compliant with the fan under test features.

III. RESULTS AND DISCUSSION

ISO 14695:2003 reports the need to determine first the natural vibration frequency of the structure used to perform vibration measurements. The common method used to obtain such information is the so called *hammer test* [18], [19].

The identified natural frequency can be neglected from the vibration analysis as dependent only on the structure used to support the fan but not on the fan itself. The test is performed by analyzing the displacement measured with the accelerometer in P_1 position. A DFT is then computed on the Y axis of the collected measurement and the result is reported in Fig. 3.

figures_paper/TestMartello_DispY_10P3.eps

Fig. 3. Hammer test: DFT computed on the Y axis signal in the reference position P_1.

The main peak in Fig. 3 represents the natural frequency of the structure. The value is $5.6\,\mathrm{Hz}$ and it can be neglected from the vibration analysis. As both the rotation speed and the displacement measurements are obtained by computing the DFT and taking the highest peak value, the peak related to the natural frequency will not be considered.

A. Fan rotation speed results

The fan rotation speed can be obtained from the three different sensing methods involved in this work: laser tachometer, piezoelectric accelerometer, and radar sensing. The laser tachometer is considered the reference sensor, the accelerometer can provide the rotation speed by analyzing the provided vibration signals, and the same is also done with the radar vibration measurements. To obtain the rotation speed from the laser tachometer, a MATLAB built-in function called *tachorpm* is used. The analog signal provided by this sensor is sampled with the same sampling frequency of the accelerometer signals (e.g $20\,\mathrm{kHz}$), then the number of RPM value obtained is much bigger than the ones obtained with the accelerometer and the radar. With the accelerometer, 88 RPM measurements are obtained and 35 with the radar. The laser tachometer directly provides an RPM measure on the collected samples. In contrast, in the case of the accelerometer and the radar, a DFT is computed. To have a fair comparison, only 88 values of RPM are considered for the laser tachometer. The RPM measure from the accelerometer is obtained considering only the Y axis, as the radar sensor can measure vibrations only in that direction. Computing the DFT directly on the acceleration provides a spectrum useful to obtain the RPM measure. An example is reported in Fig. 4.

Observing the marker values in Fig. 4, the highest peak is not the one usable to measure the RPM. To perform the measurement with the acceleration, a low-pass filtering is needed. Such a process can be tricky as the same filtering can affect the vibration measure, which is the second aim of this work. Also, the filter makes the method less generalizable as the RPM value must be known a priori. Performing the same analysis on the displacement measure can solve the problem as the second peak, after the double integration process, becomes negligible as shown in Fig. 5.

figures_paper/dft_acc.eps

Fig. 4. DFT computed on the Y axis acceleration signal. The highest peak does not provide the right RPM measure.

figures_paper/dft_disp_acc.eps

Fig. 5. DFT obtained from the accelerometer displacement measure. The first peak is related to the structure's natural frequency.

The same approach can be used on the vibration signal obtained from the radar. Differently from the accelerometer or the laser tachometer, where the signals are obtained continuously in time, with the radar one needs to perform short acquisitions and, from them, to derive the displacement vibration signal. The reason is that the amount of data generated by a radar sensor can be difficult to process if the acquisition is too long. Due to this, 35 acquisitions are performed and, from them, a vibration signal is extracted. From each acquisition, a DFT can be computed and the highest peak used to obtain the RPM measure (see Fig. 6).

From the RPM measures obtained with the three methods, the mean value and the Type A uncertainty, indicated with u_a, can be calculated [20]. Considering the laser tachometer as a reference, the error (intended as the absolute difference of the figures_paper/dft_disp_rad.eps

Fig. 6. DFT computed on the displacement vibration signal. The highest peak is used to measure the RPM of the fan with the radar.

measured values) of the other two methods can be calculated and indicated with e. In Tab. II the results are reported.

TABLE II
RPM MEASUREMENT RESULTS

Sensor	Mean Value [RPM]	u_a [RPM]	e [RPM]
Laser Tachometer (ref.)	4464.9	0.1	-
Accelerometer P_1	4261	78	203
Accelerometer P_2	4352	45	112
Accelerometer P_3	4115	104	349
Radar	4404	5	60

The results summarized in Tab. II demonstrate that the radar is a more accurate sensor than the accelerometer in measuring the rotation speed of the fan. The radar method also exhibits a lower Type A uncertainty (u_a) than the accelerometer one.

B. Displacement measurement results

The displacement measure is useful in this application to obtain information about any defect in the fan fabrication. In fact, the device can rotate with a speed that falls in the RPM tolerance region, while being affected by manufacturing defects that are revealable with a displacement measure [1], [2]. To validate the radar results, a comparison with the accelerometer is made, for the reference positions P_1, P_2 and P_3. The displacement values are obtained directly considering the highest peak of the computed DFT, both for the displacement signal collected from the Y axis of the accelerometer and the radar. The results are reported in Tab. III, where the mean displacement value, indicated with μ_d, and the Type A uncertainty (u_a) are reported.

TABLE III
DISPLACEMENT MEASURE RESULTS

Sensor	μ_d [µm]	u_a [µm]
Accelerometer P_1	25	1
Accelerometer P_2	32.2	0.1
Accelerometer P_3	7	3
Radar	29	4

Analyzing the displacement measure case, the radar performance, in terms of uncertainty, is in the order of μm. For the accelerometer, the values of u_a are dependent on the measurement position. Apparently, the radar exhibits the worst uncertainty, but the focus of the analysis can be moved from each obtained value with its u_a, to a mean displacement evaluation. In fact, it is possible to assert that the radar measured displacement is a mean between the displacement values measured by the accelerometer in the positions P_1 and P_2. The position P_3, actually, falls outside the azimuth $3\,\mathrm{dB}$-beamwidth of the radar antenna diagram. This makes that position not detectable by the radar, and its vibration is not captured by the radar displacement result.

What is obtained demonstrates the capability of the radar to be used for displacement measurements devoted to quality inspection. At the same time, it is demonstrated how the radar installation in the setup needs attention, as it influences the amount of fan surface detected by the radar, and consequently the mean vibration displacement measured.

IV. CONCLUSIONS

In this work, an alternative production line quality inspection methodology, based on a mmWave radar sensor, is investigated. The device under test is a defect free industrial fan. Two quantities are measured: rotation speed expressed in RPM and displacement vibration. To validate the radar method, the setup involves two reference sensors: a laser tachometer and a piezoelectric accelerometer.

The results obtained for the rotation speed measure demonstrate the reliability of the radar in measuring the fan RPM. The radar and the accelerometer signals are processed with a DFT and the RPM measure is obtained from them. The acceleration is not suited for this type of measure as the highest peak is not the one related to the rotation speed, as demonstrated in section III-A. For this reason, the acceleration is converted into displacement. The results reported in Table II demonstrate how the radar has better performance than the accelerometer in measuring the rotation speed. Displacement results reported in Table III show that the radar has a worse uncertainty than the accelerometer. It is observed that the radar measurement is related to the azimuth $3\,\mathrm{dB}$-beamwidth, as the vibration measured in P_3 is not included in the radar evaluation. The mean displacement value, obtained by the radar, is the mean between the vibration displacements in positions P_1 and P_2.

The radar can be an alternative sensor to improve the industrial fan quality inspection process, providing fast and reliable measures. Further investigations are needed to model how the sensor field of view influences the displacement measure.

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