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APPLICATION OF MEMS ACCELEROMETERS FOR MONITORING THE STATE AND OPERATIONS OF VEHICLES

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Abstract. Currently, several areas of the industry use vibration analysis not only to aid and plan maintenance, but also to monitor operations. The MEMS (micro-electro-mechanical systems) technology assists in several applications in this area, given its accessibility and low cost. Thus, the analysis of vibrations is seen as a possibility of monitoring operations in vehicle fleets. The interest of this work was to evaluate the possibility of using inexpensive accelerometers and MCUs (microcontroller units) for collecting and evaluating the operating conditions of automotive vehicles, monitoring basic parameters such as engine speed and other systems activation. A low cost acquisition set was developed using an ESP32 chip development board and a MEMS type accelerometer model MPU6050, fixed on an internal combustion engine vehicle. The acquisition system was programmed to operate recording the data sampled in a SD card for later evaluation using a computer or performing the FFT (fast Fourier transform) of the signal and returning the frequencies with the highest amplitudes through the serial port. The work was initially carried out under static conditions and later with the vehicle on a known route. The results obtained were compared with the information recorded via the vehicle's CAN (Controller Area Network) data, verifying the potential use of the proposed system for this application.

Keywords: MEMS Accelerometers, Monitoring, CAN bus, Vibration analysis

1. INTRODUCTION

As described by Heuberger *et al.* (2011), microelectronics has been the driver of innovations in various sectors of the industry, being classified as the main responsible for such innovations. Furthermore, thanks to the development and advancement of modern manufacturing technology, microelectromechanical systems have been able to achieve many complex applications and intelligent systems, without giving up their low cost.

Directly related to the technological advance generated by the development and expansion of microelectronics, we have productivity gains in several sectors and areas. Among them, there is the vehicle fleet monitoring sector, which this work focuses on.

This feature is already a reality in many companies that have vehicles for various applications, such as executive/business transport, car rental companies, urban private transport by app companies and cargo transport companies. According to Zanella *et al.* (2020), the use of a fleet monitoring system is very important in various vehicle management situations, presenting significant gains with the reduction of operating costs, as presented by Arruda Júnior (2014).

However, the use of the CAN network for monitoring vehicles parameters is sometimes not desired in certain situations, such as in the cases where the insertion of external equipment to the vehicle CAN network results in loss of warranty. Furthermore, as in the cases described by Tironi *et al.* (2011), the use of the CAN network can be a gateway to vehicle system full invasions, or at least of some systems, which even when simple, like the sound systems and power windows, they can present certain risks to the driver.

Most fleet monitoring systems are limited to monitoring basic parameters such as speed and positioning when they do not make use of the data available on the vehicles CAN network. For this, the systems normally use GNSS (Global Navigation Satellite System) and INS (Inertial Navigation System) or just one of them. In these cases, the monitoring of the vehicle's operating status, such as the rpm range in which the engine works, is not performed.

Thus, this work is intended to evaluate the possibility of applying low cost MEMS-type accelerometers in fleet monitoring systems, not only to assess the movement of vehicles, as is already done, but also to monitor their operating status in systems that do not count or wish access to the CAN network for monitoring parameters such as engine speed and systems activation.

2. LITERATURE REVIEW

In this section, a brief literature review will be carried out regarding MEMS accelerometers.

2.1 MEMS Accelerometers

The growing demand for sensors applicable to vibration monitoring and analysis has increased the necessity and demand for alternatives to high-cost conventional accelerometers (Albarbar and Teay, 2016).

Recent works have studied the replacement of piezoelectric accelerometers by MEMS capacitive accelerometers, being used in the most varied types of applications. According to Korvink and Paul (2006) MEMS devices are considered to be the smallest machines created by humans, and the cost of such devices can generally reach the max of tenths of the values practiced in the cheapest conventional accelerometers available in the market (Albarbar *et al.*, 2008).

Regarding its functioning, MEMS accelerometers are transducers that transform mechanical energy into electrical signals, being the system acceleration its source of information. They basically consist of three fundamental structures: an inertial mass, flexible structures and stationary fingers structures. The stationary fingers are on both sides of the test mass, having the same capacitance value in a mechanical equilibrium position of the set. When subjected to an acceleration, the inertial mass that is physically connected with the capacitor plates moves, changing the distance or the area between the capacitive fingers, thus changing the capacitance of the assembly. This capacitance value is proportional to the acceleration applied to the system (Tez and Akin, 2013).

3. MATERIALS AND METHODS

3.1 Acquisition System

In this subsection, some of the components present in the system assembled to carry out the experimental tests will be described, which was basically composed by a microcontroller, a MEMS accelerometer, a SD card module, an OBD-II adapter, an internal combustion vehicle and a computer. Its main characteristics will be presented as well as the reasons for each choice.

3.1.1 Accelerometer - MPU6050

To be part of the acquisition set, the selected MEMS accelerometer module was the MPU6050, from the manufacturer InvenSense. As shown in the work by Ribeiro and Lameiras (2019), most of the different MEMS-type accelerometer models evaluated performed well in general situations for SHM (Structural Health Monitoring), including the MPU6050 digital accelerometer, commonly found on the GY-521 breakout board.

Among the reasons for its selection to integrate the project are its low cost, its wide application in scientific projects in the engineering area, and its availability in the stock. This model has a three-axis MEMS-type accelerometer and gyroscope coupled on a single chip, in addition to a temperature sensor, with the I2C (Inter-Integrated Circuit) standard communication protocol.

In addition, the breakout board operates with a voltage of 3 V to 5 V, with a 16-bit analog-to-digital converter. Figure 1 illustrates the GY-521 module containing the mentioned 6 DOF (Degrees Of Freedom) MPU6050, with some general characteristics of the MPU6050 provided by Invensense (2013) presented in Tab. 1.

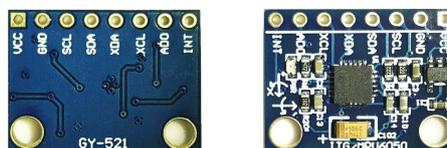


Figure 1. MPU6050 MEMS module board with accelerometer and gyroscope.

Table 1. GY-521 Breakout board characteristics

Main Chip	Max Sample Rate (SR) [kHz]	Accel. Cross-Axis Sensitivity	Accel. Noise Performance [$\mu\text{g}/\sqrt{\text{Hz}}$]	Ranges		Board Dimensions [mm]
				Gyros [$^{\circ}/\text{s}$]	Accelerometers [g]	
MPU-6050	Accels: 1 Gyros: 8	+2%	400 ⁽¹⁾	$\pm 250, \pm 500, \pm 1000, \pm 2000$	$\pm 2, \pm 4, \pm 8, \pm 16$	20 x 16 x 1

⁽¹⁾ Using $\pm 2\text{g}$ range and SR = 1kHz.

3.1.2 Microcontroller - ESP32

For the project in question, the development platform of the Espressif Systems family, called ESP32, was selected as the hardware for data acquisition. This choice was made based on the cost-effectiveness of the set, given the sufficient number of GPIO (General Purpose Input/Output) available, use of a microcontroller with two cores, in addition to the superior performance in processing when compared to devices with similar proposals, such as Arduino family platforms available on the market. Some basic features provided by Espressif (2021) of the MCU (Microcontroller Unit) are shown in Tab. 2.

Table 2. ESP32 module characteristics.

MCU Chip	Max Frequency [MHz]	Flash Memory [MBytes]	GPIOs	Hardware Ports ⁽¹⁾	Operation Voltage [V]	Input Voltage [V]	Operation Temperature [°C]
Xtensa Dual-Core 32bit LX6	240	4	36	4 / 2 / 2 / 3	3.3	4.5~9	-40 ~125

⁽¹⁾ Presented in the following order: (SPI / I2C / I2S / UART).

3.1.3 Eletronic Circuit

The electronic components selected to compose the acquisition set were connected together in order to meet the modules configurations, using GPIOs suitable for I2C and SPI communication ports respectively for the accelerometer and memory card modules. The final connection scheme between the components is showed in Fig. 2.

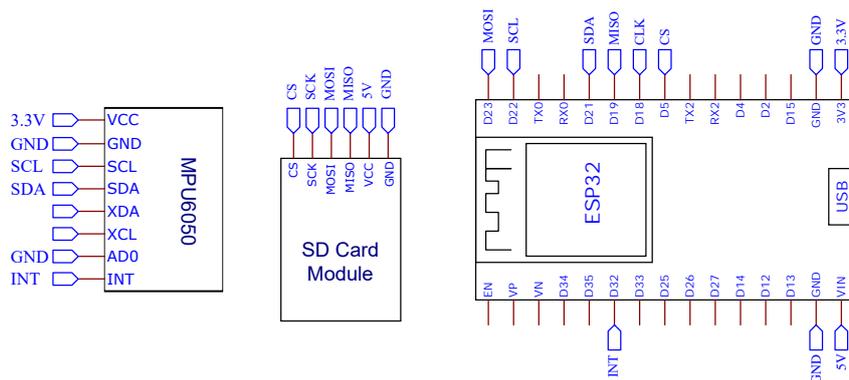


Figure 2. Electronic schematic diagram.

The circuit was powered by the USB connection of a notebook unplugged from the wall outlet whenever used to carry out the tests. The set was initially assembled on a breadboard to verify its connections and the correct functioning of the code, being later transferred and welded to a prototype board, to ensure a correct connection between the components.

3.1.4 Program Code

With the hardware set ready, it was programmed using Arduino's IDE (Integrated Development Environment), developing the code in C++ language. A single code was written, enabling the selection of the operating mode through the serial communication for each experimental development stages. Basically, the written code has three types of operating mode, denominated:

- Calibration: Calibration of the MPU6050 using the settings described in the manufacturer's datasheet;
- Data logging: The ESP32 acts as a data logger, reading the acceleration data from the sensor and storing it in the memory card module of the set;
- Real-time evaluation: In this mode, the microcontroller evaluates the signals sampled in the frequency domain, performing the FFT internally, presenting its evaluation in serial communication and storing in the SD card the predominant frequency values, with greater amplitude in the spectrum, and the time required for each evaluation.

Specifically in the "Real-time evaluation" mode, the possibility of changing the number of points sampled was allowed, but the default value used in all steps performed was using samples of 512 points. In all operating modes described, the accelerometer was set to a sampling frequency of 1000 Hz, the maximum acceleration sampling frequency of the MPU6050.

The code developed also allowed the selection of the operating range of the accelerometer using serial communication with the computer, in any of the modes, using the $\pm 8g$ mode by default in all modes.

Thus, knowing the sampling frequency of the acquisition system and the number of points collected for the "Real-time evaluation" mode, according to the Nyquist sampling theorem, the set allows an evaluation in the frequency domain of a 500 Hz spectrum, featuring frequency bins of approximately 2 Hz.

3.1.5 OBD-II - ELM327

As a comparison parameter of the experimental data obtained using the proposed system with the MEMS accelerometer, an OBD-II adapter model ELM327 V1.5 was used to communicate with the vehicle's CAN network. This adapter features an integrated PIC18F25K80 microcontroller and serial communication via Bluetooth 2.1. Its choice was made based on its availability in several auto repair shops, low cost and applicability in several FIAT brand vehicles, satisfying the Punto model selected for the tests.

3.1.6 Vehicle - Punto HLX

To carry out the proposed tests, a FIAT brand vehicle, model Punto HLX 1.8 8v, was used. This vehicle has a 1796cm³ SOHC transverse engine, four-stroke and four cylinders. The injection and ignition system is controlled by a Delphi multipoint sequential central unity. Some other features of the engine are shown in Tab. 3.

Table 3. Characteristics of the vehicle engine used.

Engine Displacement [cm ³]	Cycle	Cylinders Ignition Order	Bore x Stroke [mm]	Compression Ratio	Maximum Power [cv] (rpm)	Maximum Torque [kgm] (rpm)	Idle Speed [rpm]
1796	OTTO	1-3-4-2	80.5x88.2	10.5±0.3:1	115 (5500)	18.5 (2800)	900±50

Font: (FIAT, 2008)

Additionally, it is described in the vehicle manual that its cooling system has a two-speed fan to help cool the engine set (FIAT, 2008). Nothing is said about what are the two operating speeds. Although not mentioned in the user manual either, the vehicle has a communication port with the CAN network in OBD-II standard next to the internal fuse compartment.

3.2 Experimental Procedures

Initially, with the module already externally calibrated following the registration maps of the MPU6050, described by Invensense (2013), the acquisition set was installed in the vehicle. The prototype board containing the ESP32 microcontroller and the SD Card module was positioned inside the vehicle, connecting it to a notebook for power. The GY-521 module was positioned under the hood, over the plastic engine protection cover. The connection between the accelerometer module and the acquisition board inside the vehicle was made using a 8-way cable, with a length of approximately 2 m. Figure 3 shows the positioning of the accelerometer module on the plastic cover of the engine, indicating the orientation of the axes, with the X aligned longitudinally with the car.

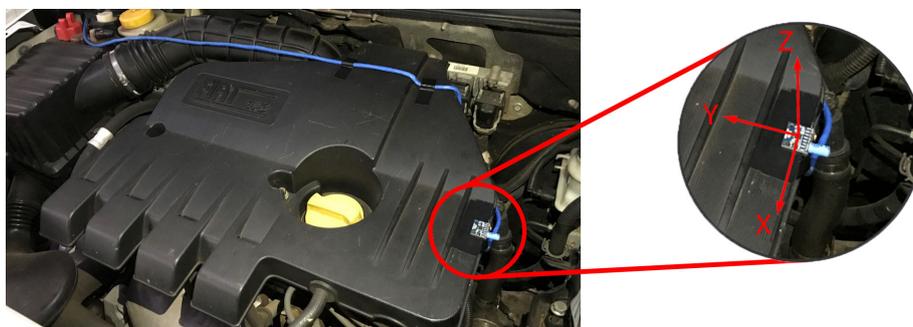


Figure 3. Positioning of the accelerometer module.

In addition to the developed system, the ELM327 adapter was also installed to read the vehicle's CAN network parameters. For this, it was necessary to have access to the OBD-II port in the vehicle's fuse compartment, enabling the bluetooth connection with the computer after turning the vehicle's ignition key in the "MAR" position.

After the installation process of the equipment in the vehicle, the experimental work procedure was basically divided into three major steps, namely:

- Engine speed evaluation under static conditions: data collection using the proposed system with the vehicle parked, starting the engine and evaluating the capacity to measure its rotation speed with the MEMS accelerometer.
- Fan State Evaluation Under Static Conditions: Evaluation of the two operation stages of the radiator fan with the vehicle parked, identifying the predominant frequencies for each speed of its operation.
- Engine speed evaluation with the vehicle in motion: Verification of the possibility of monitoring the engine rotation speed with the vehicle performing a known route using the same set applied for the evaluation under static conditions of the vehicle.

3.3 Engine Speed Evaluation Under Static Conditions

3.3.1 Offboard Signal Processing

With the set properly installed in the vehicle, the initial evaluation of the MEMS accelerometer for the static operating condition was performed. Using the microcontroller applying "Data logging" mode programmed, acceleration data were collected, starting with the engine off. After the start of recording, the car's engine was also started, waiting the stabilization of the idle speed, followed by accelerations and decelerations of the engine, returning to idle before the shutdown and completion of data recording.

Parallel to the collection of data from the developed acquisition set, the parameters taken as a reference by the vehicle's CAN network were read and recorded from the ELM327 adapter connected via bluetooth with the computer, storing such values.

Once the data was collected, the signals were processed and analyzed using a Python script running on a computer. The data were then crossed with the values obtained by the CAN network, evaluating the system performance for this operational condition.

3.3.2 Onboard Signal Processing

In the second stage of the engine evaluation under static conditions, the "Real-time evaluation" mode was applied to the microcontroller, as previously described. Again, the MEMS accelerometer system was started with the vehicle engine off, followed by starting, accelerating and decelerating, ending with idling and finishing with the engine shutdown. For this case, the CAN network parameters were also recorded jointly by the computer, comparing the results at the end of the test.

The time required by the microcontroller for the data processing in this operation mode was also evaluated.

3.4 Fan State Evaluation Under Static Conditions

Since the activation of the cooling system fan is done only in specific cases, such as activating the air conditioning system or reaching certain conditions of temperature and vehicle speed, it was necessary to inject some codes into the vehicle's CAN network. Thus, it was possible to make the fan operate at the two speeds available for the refrigeration system even with the vehicle's engine turned off using the OBD-II adapter.

With the set operating in a similar way to the one used in the engine speed evaluation step under static conditions, the vehicle radiator fan was activated, recording the accelerometer data on the SD card. Again, the acceleration data collected were evaluated using the developed Python code, defining the predominant frequency in the spectrum for each fan operating state.

3.5 Engine speed evaluation with the vehicle in motion

For the step of evaluating the system's capacity to monitor the engine rotation speed with the vehicle in motion, the acquisition set was kept with the same settings used in the previous steps. First, the vehicle was put in motion, being initially driven in an urban route, collecting data from the MEMS accelerometer and engine rotation via the CAN network, reading data from the ECU (Engine Control Unit), from its start, departure, until its shutdown.

Subsequently, the vehicle was driven on a highway route, again starting at rest, accelerating, and decelerating to a stop point. For both the urban route and the highway condition, the acquisition set was used in the "Data logging" mode, with the data being processed and evaluated later in the code developed in Python.

4. RESULTS AND DISCUSSION

4.1 Engine Speed Evaluation Under Static Conditions

Since the four-cylinder, four-stroke internal combustion engine of the vehicle operates in such a way that for each complete revolution of the crankshaft two combustions pulses are generated per pair of cylinders out of phase with

each other, it is known that under normal operating conditions the engine's predominant frequency should be twice its crankshaft rotation. Thus, for all comparisons made between the signals coming from the accelerometer and the parameters read on the vehicle's CAN network, the engine speed values were passed from rpm to Hz.

4.1.1 Offboard Signal Processing

Plotting the sampled acceleration data with the vehicle in parked condition, and performing the FFT of the signals, the graph shown in Fig. 4 was obtained.

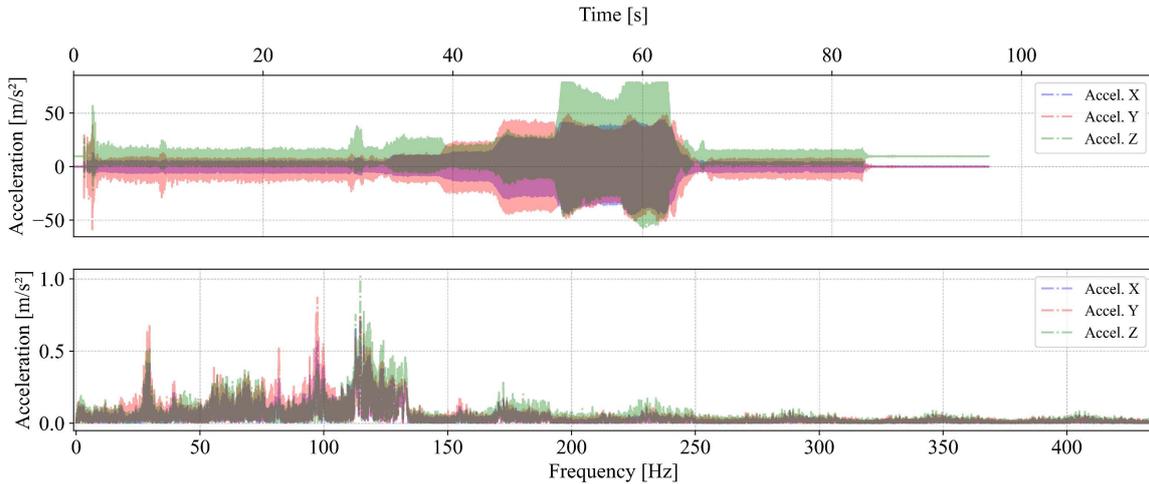


Figure 4. Complete sampled signal in the time and frequency domain.

Figure 5 shows the spectrogram of the signal sampled in the X direction using the MPU6050 and the superposition of the data obtained by the CAN network. The frequency axis was adjusted for better visualization of the range of interest.

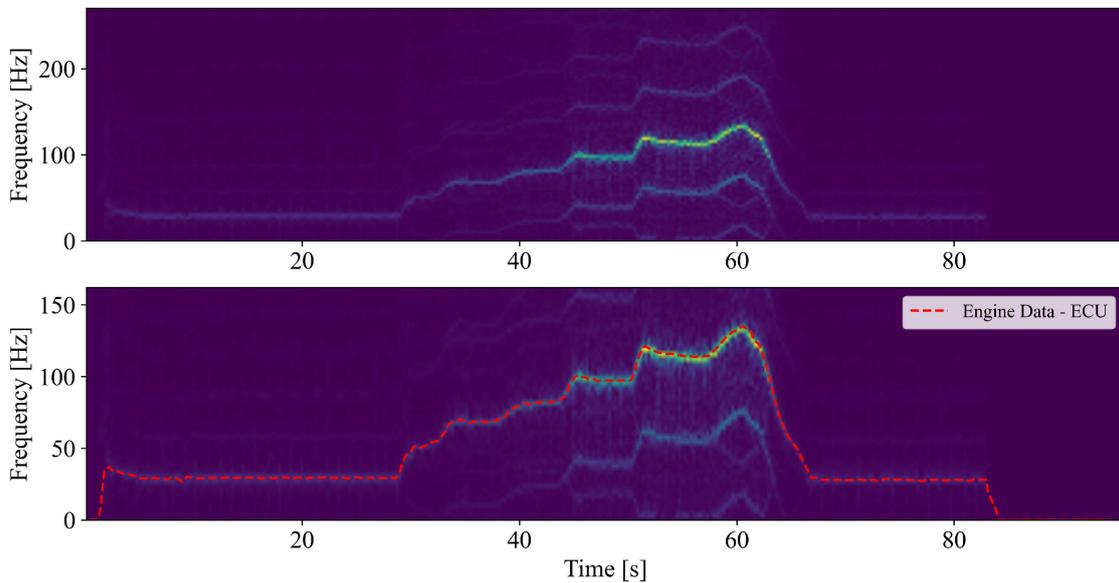


Figure 5. X-axis acceleration signal spectrogram using the MEMS accelerometer compared to the true engine speed obtained from the CAN network.

As can be seen in the generated spectrogram, it was possible to observe an excellent correspondence between the signal sampled with the accelerometer and the real engine speed. The other shadows of the main signal are just multiples of the main component as they represent harmonics and vibration from other sets.

4.1.2 Onboard Signal Processing

The data obtained using the microcontroller's "Real-time evaluation" mode can be seen coupled with the data from the vehicle's CAN network in Fig. 6.

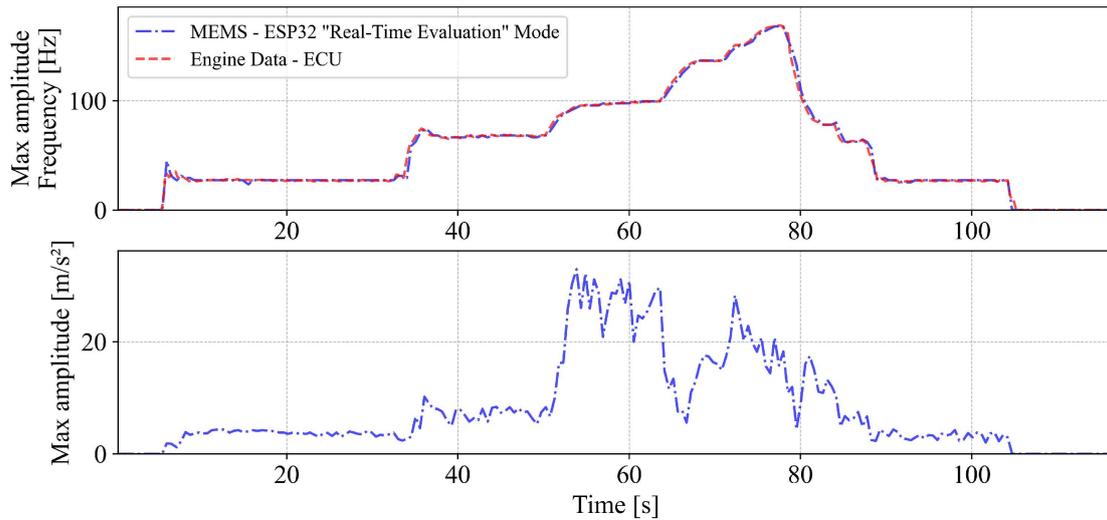


Figure 6. Microcontroller results processing the acceleration signals from the MPU6050 against the true engine speed values.

Analyzing Fig. 6, it is possible to verify that the signal processing using the selected microcontroller and the code developed for it allows the onboard evaluation of the engine rotation speed without the need to access the vehicle's CAN network, using only non-invasive low-cost equipment. The correspondence between the rotation evaluated using the MEMS accelerometer and that obtained from the ECU through the OBD port was again considered satisfactory for the proposed application.

The time taken by the microcontroller to perform the FFT on 1000 groups of signals sampled at the standard speed of 1000 Hz and 512 points was evaluated, obtaining an average value of 1.50 ± 0.01 ms per sample, much less time than that taken to sample the signal.

4.2 Fan State Evaluation Under Static Conditions

The signals sampled for evaluating the radiator ventilation system under static conditions are shown by Fig. 7 in the time domain and in the frequency domain, processed using Python code.

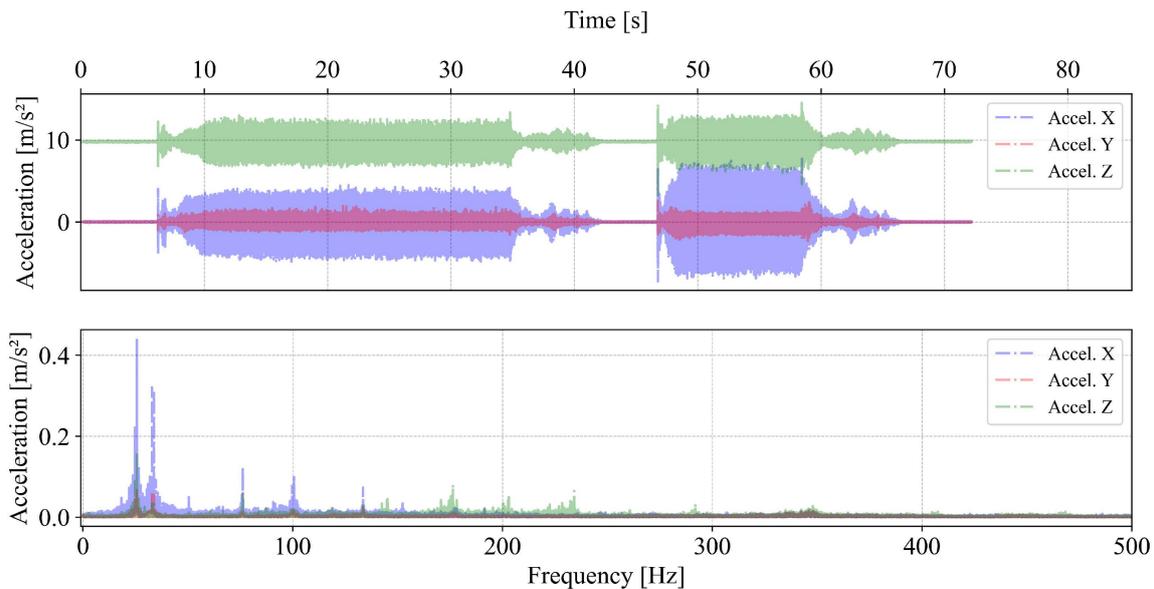


Figure 7. MEMS accelerometer signal in the time and frequency domain for fan activation.

Plotting the x-axis acceleration signal in a spectrogram coupled with the injected fan stages into the vehicle's CAN network using the OBD adapter, the graph shown in Fig. 8 was obtained.

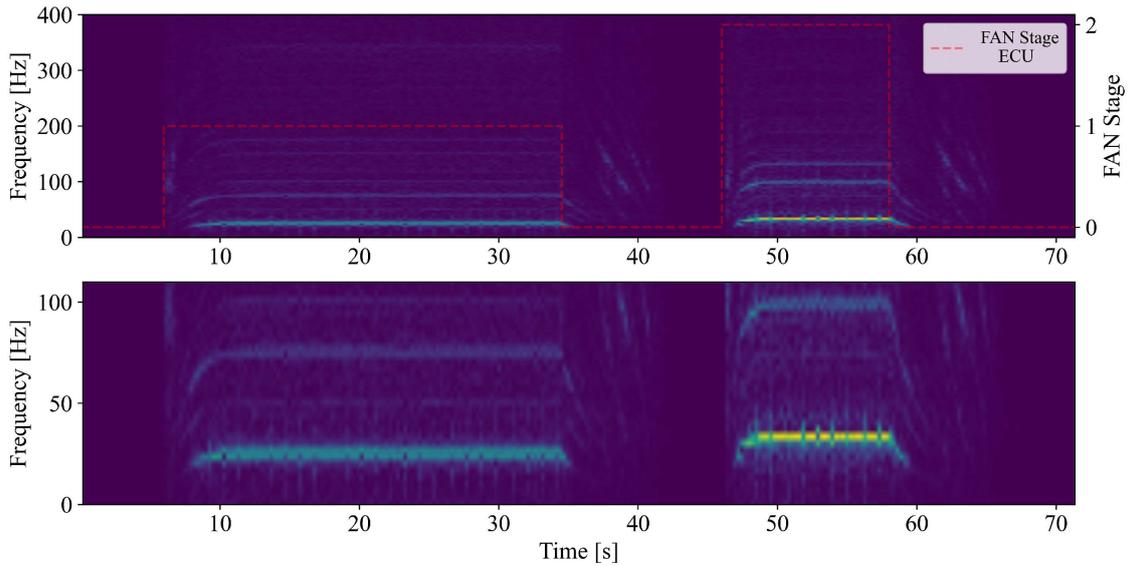


Figure 8. X-axis acceleration signal spectrogram compared to triggered fan stages.

Analyzing the figures, from the spectrum of the signal in frequency and the spectrogram of the acceleration in X, it was possible to verify the ability to identify the activation of the fan at its two speeds, estimating a characteristic frequency around 25 Hz for the first stage, and from 33 Hz to the second.

4.3 Engine Speed Evaluation with the Vehicle in Motion

For the first evaluation of the engine speed monitoring capability using the MEMS sensor with the vehicle running on an urban route, the data presented in Fig. 9 were obtained both in the time domain and in the domain frequency.

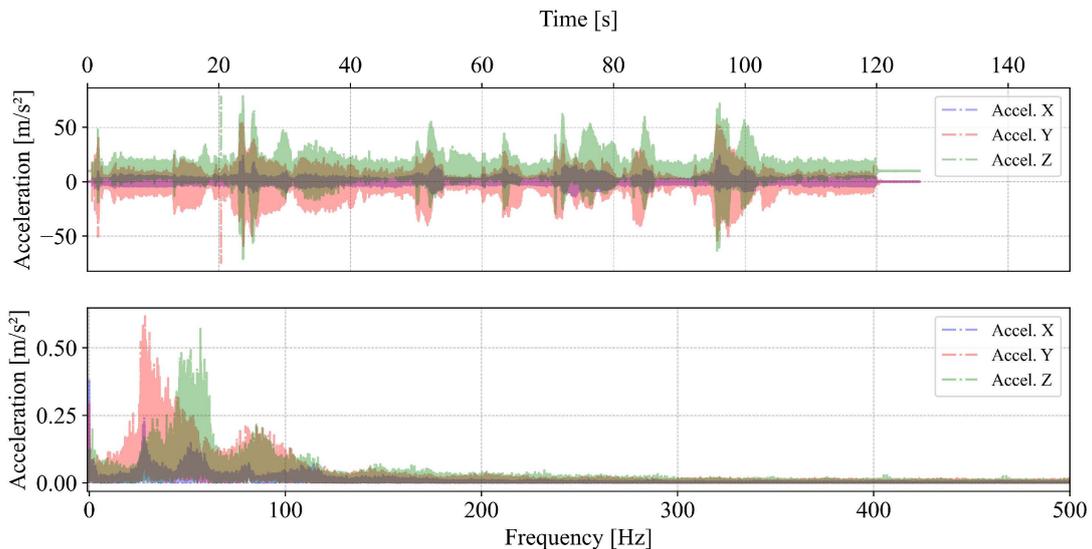


Figure 9. Sampled signal in the time and frequency domain for the first test route.

Again, it was noted that the sensor signal did not saturate on any of the axes operating in the range of $\pm 8g$. For a better understanding of the result, the X-axis acceleration signal spectrogram was generated, as shown in Fig. 10. Comparing with the rotation data collected from the ECU via CAN network for the same route, an excellent relation between the data is noted, verifying the possibility of applying the sensor for this operating condition. The frequency axis was adjusted for a better visualization of the range of interest.

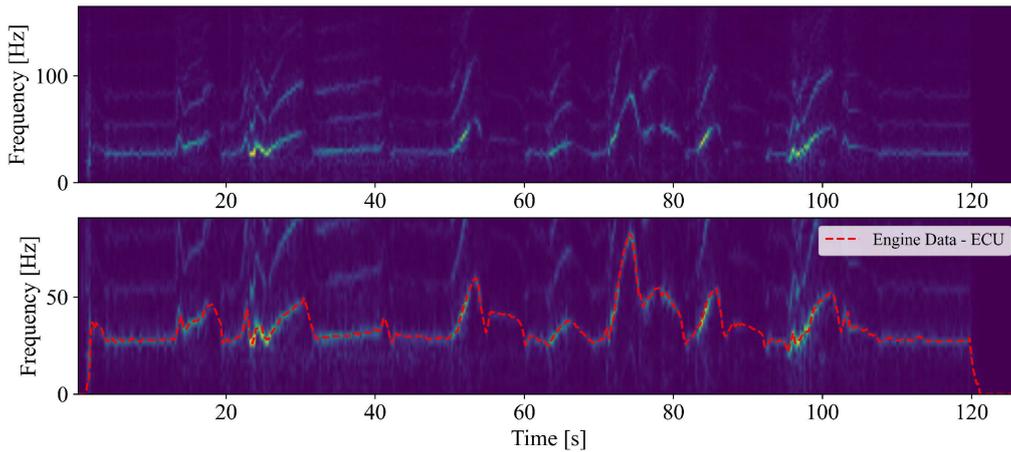


Figure 10. X-axis acceleration signal spectrogram compared to the true engine speed obtained from the ECU over the CAN network for the first route.

Finally, to evaluate the sensor with the vehicle running on the highway route, the MEMS sensor data were collected, which are shown in Fig. 11. As observed, there was also no signal saturation with the sensor operating in the $\pm 8g$ range.

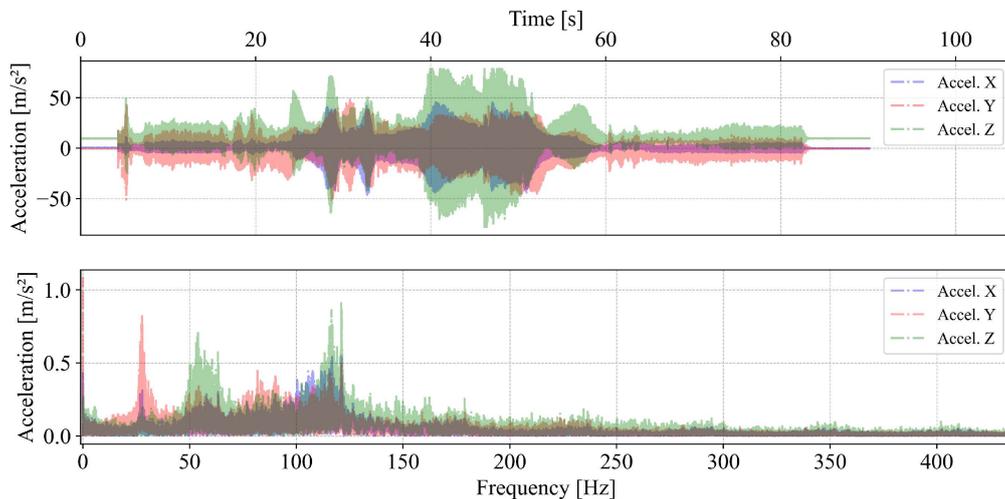


Figure 11. Sampled signal in the time and frequency domain for the second test route.

Figure 12 shows the spectrogram of the acceleration signal again in the X direction. Together are plotted the engine speed and vehicle speed data obtained from the ECU over the CAN network. The frequency axis was adjusted for better visualization of the range of interest.

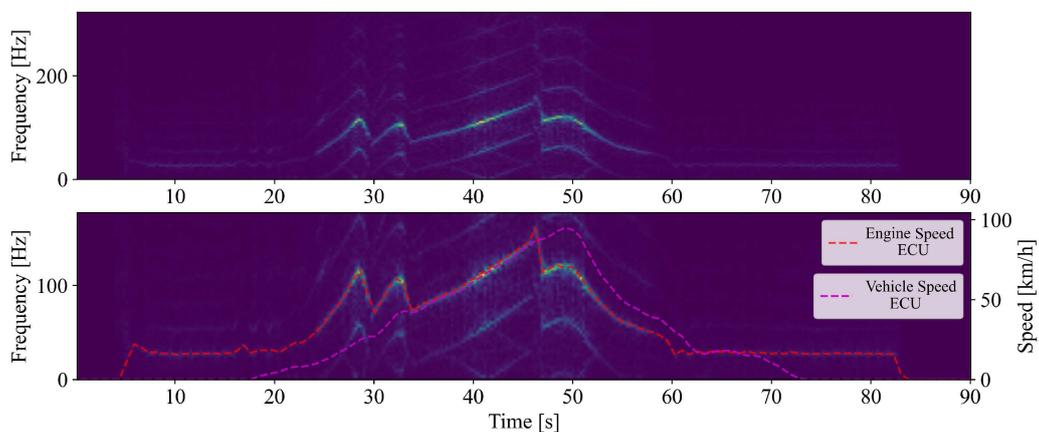


Figure 12. X-axis acceleration signal spectrogram compared to the true engine speed and vehicle speed obtained from the ECU over the CAN network for the second route.

Again, there was a correspondence between the operating engine speed data for the evaluated highway route.

Thus, the association of this vibration analysis system with conventional monitoring systems using INS and GNSS, it is possible to assess how the vehicle is being driven by the driver. Comparing vehicle speed ranges, determined by GPS, for example, and engine speed, determined by the MEMS-type accelerometer system proposed in this work, it is possible to assess whether the driver is within the recommended gear change ranges informed by the manufacturers of vehicles.

5. CONCLUSIONS

In all evaluations made, the accelerometer MPU6050 supported accelerations with amplitudes within its operating range without problems, even being inserted into engine compartment, place with significant electromagnetic interference. In the steps of evaluating the collected signal using the code written in Python language, the spectrograms obtained verified that the signals sampled by the accelerometer described values corresponding to the parameters read on the vehicle's CAN network, both in static conditions and with the vehicle in motion.

The selected microcontroller proved to be sufficient in signal processing for the required task, in both operating modes used. The ESP32 was able to sample the accelerometer data and evaluate the signals in the frequency domain at sufficient times for the proposed applications, confirming the possibility of associating the MEMS-type MPU6050 accelerometer with low-cost microcontrollers.

Thus, with the initial assessments carried out in this work, it is possible to say that the application of MEMS accelerometers has great potential for use in monitoring vehicle operating parameters in non-invasive monitoring systems. In general, it was possible to monitor the proposed parameters during the tests, observing success in monitoring the engine rotation under different operating conditions and detecting the activation of an auxiliary system at its two speeds under static conditions.

6. ACKNOWLEDGEMENTS

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