# Time Domain Identification of Multi-stage Planetary Gearbox Characteristic Frequencies Using Piezoelectric Strain Sensor

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**Abstract.** Nowadays, condition monitoring of gearboxes is based on analyzing vibration signal (mostly acceleration, velocity; fewer strain) measured from mechanical components or on analyzing acoustic emission and temperature data. Strain sensors are rarely used because of their high cost, mounting difficulties and their sensitivity harsh environment. They are based on strain gage technology which implements 'Wheatstone Bridge Conditioner' to be able to measure strain values. This bridge circuit, unfortunately, becomes non-linear out of the measurement range resulting in significant errors. To avoid those errors, a new technology of piezoelectric strain sensors, relatively new to condition monitoring, emerges: they have good precision since the accuracy is improved and provide good results especially when attempting to do measurements at extremes of the range. In this work, a piezoelectric strain sensor mounted on an industrial planetary gearbox (PG) in vertical direction is used to acquire time domain signals. This latter is introduced to focus on the importance of the new time domain representation of a gearbox dynamic behavior by a such sensor. Finally, an analysis of the RHM sensor time domain data is conducted to identify the PG characteristic frequencies.

**Keywords:** Planetary gearbox · Vibration signal · Piezoelectric · Strain

## 1 Introduction

Planetary gearbox are widely used either in automobiles and in industrial machinery in order to transmit the power from input shaft to output shaft with a high ratio in a compact space. Many researchers tried to characterize its dynamic behavior. It was a hard task because of the complexity of its design and motions of its parts, especially the motion of planets. They used sensors and microphones which acquire signal (vibration or acoustic) to be processed in order, for instance, to cancel the noise (masking signal) which makes analysis of the signal easier.


A. Hammami et al. (Eds.): MOSCOSSEE 2021, ACM 20, pp. 116–122, 2022.
https://doi.org/10.1007/978-3-030-85584-0_12

Noll et al. [1] applied a piezoelectric strain sensor (SG) on the external housing of the fixed ring gear. They experienced a piezoelectric sensor in AC- and DC-coupling. Results show that strain signals can be obtained even down to 0.002 Hz (low spin). The work of S. Kiddy et al. [2] shows that the surface strain is collected by the use of Fiber-Bragg-sensor mounted on the ring gear of a bell helicopter OH-58C gearbox. They compared signals for healthy and damaged cases and it was demonstrated that strain signal are useful to detect damages. Due to the proper reproducibility of the signal, there is no need to average the signal over multiple revolutions as done for signals issued from accelerometers. Zhang et al. [4] did an excessive use of strain gauges. They mounted 6 strain sensors along a shaft system test rig to identify the load on each bearing supporting the shaft. They developed a strain gauge method which can reduce the modeling error taking into account the best location of sensors where the strain is sensitive to the change of the bearing load. Oskoueian et al. [5] monitor a Mitsubishi 4 cylinders internal combustion engine block by taking measurement with strain sensor. After processing signals captured by strain sensors, they were able to localize in which cylinder the mechanical wear is. In another research focused on gear root bending stress analysis, Lisle et al. [6] used strain gauges method to validate a numerical finite element analysis (ANSYS) highlighted the advantageous of this method and to compare it with ISO 6336:2006 and AGMA 2101-D04. Yoon et al. [7] proposed a new methodology for the diagnosis of planetary gearbox faults. Considering that the amplitude modulation is less effecting strain signals, the proposed method is based essentially on processing strain signals. So, they used a piezoelectric strain sensor mounted on the external surface of a planetary gearbox ring gear. Results show that all faults made in the gearbox were identified and they were fruitful compared with whom conducted from acceleration analysis. As mentioned in literature, strain sensors (classical and piezoelectric) are used for many purposes, for instance to compare different signals acquired from the same sensor with different coupling [1], identification of health condition and fault diagnosis as investigated in [3] and [7]. This work is focused on identification of vibration sources in a multi-stage planetary gearbox in healthy case using a piezoelectric strain sensor by analyzing only the time data. This paper is organised as follows. Section 2 is dedicated to present the experimental setup. Section 3 analyses time domain signal issued from the piezoelectric strain sensor. Conclusion is drawn at the end of the paper.

## 2 Experimental Setup

Figure 1 presents the Test rig used to investigate the dynamic behavior of a three stages planetary gearbox (PG) given by its kinematic scheme in Fig. 2. The motor is operating at 1008 rpm. Passing through parallel gearbox (ratio = 1/2.91), the speed is reduced to 346,4 rpm and it is reduced again passing through the planetary gearbox to achieve 1,73 rpm at its output.

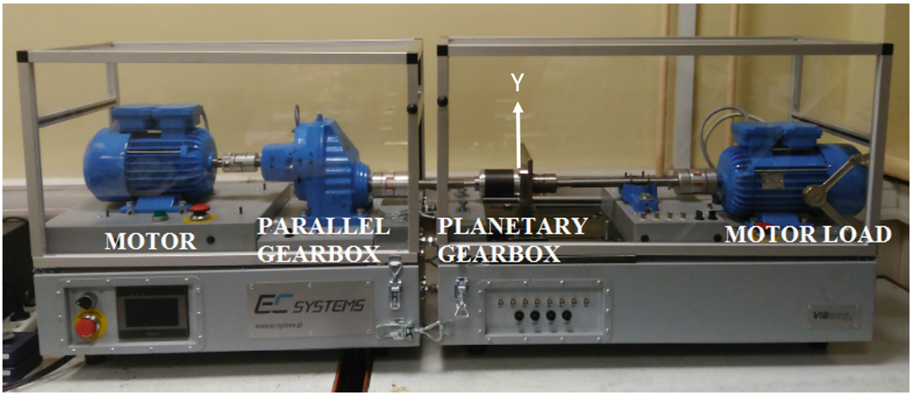


**Fig. 1.** Test rig

A quartz strain gage RHM-240A02 is attached to the PG to measure strain on Y direction as indicated in Fig. 1. It incorporates a built-in MOSFET microelectronic amplifier. This serves to convert the high impedance charge output into a low impedance voltage signal for analysis or recording. ICP quartz strain sensors, powered from a separate constant current source, operate over long ordinary coaxial or ribbon cable without signal degradation. The low impedance voltage signal is not affected by tribo-electric cable noise or environmental contaminants.

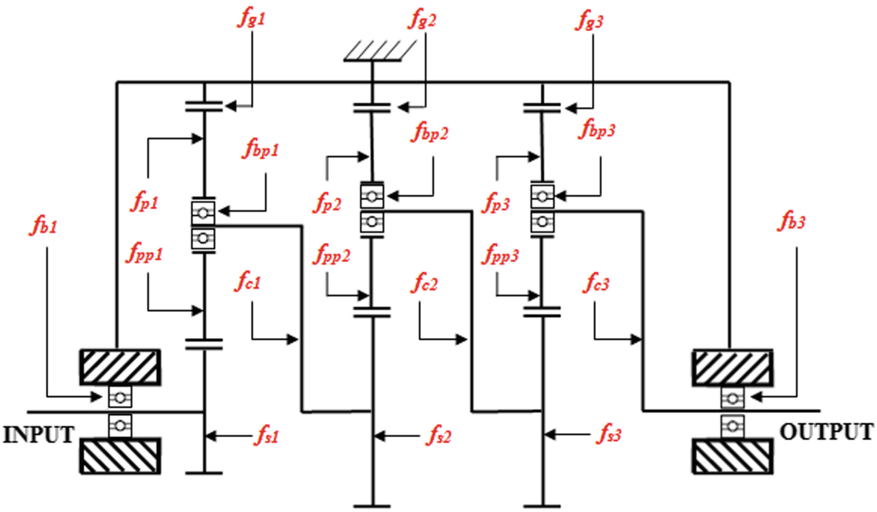


**Fig. 2.** Kinematic scheme of three stages planetary gearbox

Since the experimental conditions are given, the PG characteristic frequencies can be calculated. Those latter are given in Table 1. For more information about experimental setup, the reader can refer to the work of Zghal et al. [8].

**Table 1.** Characteristic frequencies of the three stages planetary gearbox when the motor was operating at 1008 rpm, $^{(*)}$:Parallel Gearbox

| Fr($Hz$) | Description | $1^{st}$ stage | $2^{ed}$ stage | $3^{ed}$ stage |
|---|---|---|---|---|
| $f_{si}$ | Sun gear frequency | 5.77 | 0.72 | 0.15 |
| $f_{ci}$ | Carrier frequency | 0.7223 | 0.15 | 0.03 |
| $f_{pi}$ | Planet frequency | 1.68 | 0.39 | 0.08 |
| $f_{ppi}$ | Planet pass frequency | 2.16 | 0.45 | 0.12 |
| $f_{gi}$ | Gear mesh frequency | 60.67 | 12.13 | 2.43 |
| $f_{b1}$ | Sun bearing frequency | 5.77 | – | – |
| $f_{bpi}$ | Planet bearing frequency | 0.96 | 0.25 | 0.05 |
| $f_{b3}$ | Carrier bearing frequency | – | – | 0.03 |
| $f_{in}$ | Pa.G$^{(*)}$ input frequency | 16.78 | | |
| $f_{out}$ | Pa.G output frequency | 5.77 | | |
| $f_{gpg}$ | Pa.G gearmesh frequency | 386.4 | | |

## 3 Time Domain Identification

In the previous section, all PG characteristic frequencies are calculated theoretically by using equations based on its kinematics. In this section, data collected from the Piezoelectric strain sensor RHM240A02 is presented. The chosen time signal is analyzed in order to identify the calculated frequencies in the previous section. This step will allow us checking the efficiency and robustness of the use of the strain sensor in describing PG vibration sources. The processing is simple and described as the following: we present the row signal than we do multiple zoom section to identify repetitive behavior. Figures 3 and 4 present all repetitive oscillations in the acquired strain signal.

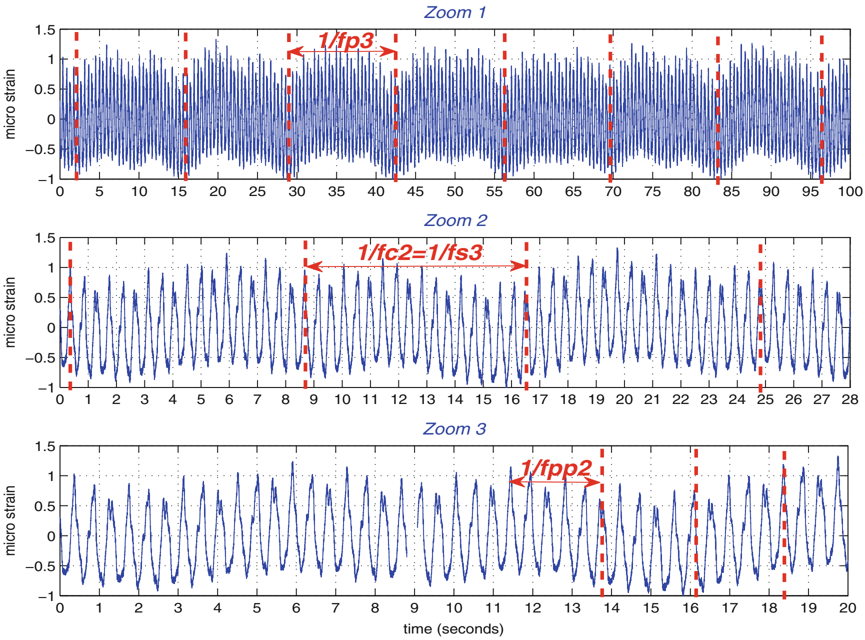


**Fig. 3.** First three zoom sections

Identified frequencies are summarized in Table 2.

The checked values are those identified previously. As shown, almost 40% of characteristic frequencies are identified from only the time domain representation. Hence, this piezoelectric strain sensor shows 40% of the planetary gearbox dynamic behaviour since the collected time signal reproduces with a good accuracy what was really happening inside the gearbox.

**Table 2.** Summary of the identified frequencies

| Frequencies($Hz$) | Description | $1^{st}$ stage | $2^{ed}$ stage | $3^{ed}$ stage |
|---|---|---|---|---|
| $f_{si}$ | Sun gear frequency | 5.77 | 0.72 ✓ | 0.15 ✓ |
| $f_{ci}$ | Carrier frequency | 0.72 ✓ | 0.15 ✓ | 0.03 |
| $f_{pi}$ | Planet frequency | 1.68 | 0.39 | 0.08 ✓ |
| $f_{ppi}$ | Planet pass frequency | 2.16 | 0.45 ✓ | 0.12 |
| $f_{gi}$ | Gear mesh frequency | 60.64 ✓ | 12.13 ✓ | 2.43 |
| $f_{b1}$ | Sun bearing frequency | 5.77 | – | – |
| $f_{bpi}$ | Planet bearing frequency | 0.96 | 0.25 | 0.05 |
| $f_{b3}$ | Carrier bearing frequency | – | – | 0.03 |

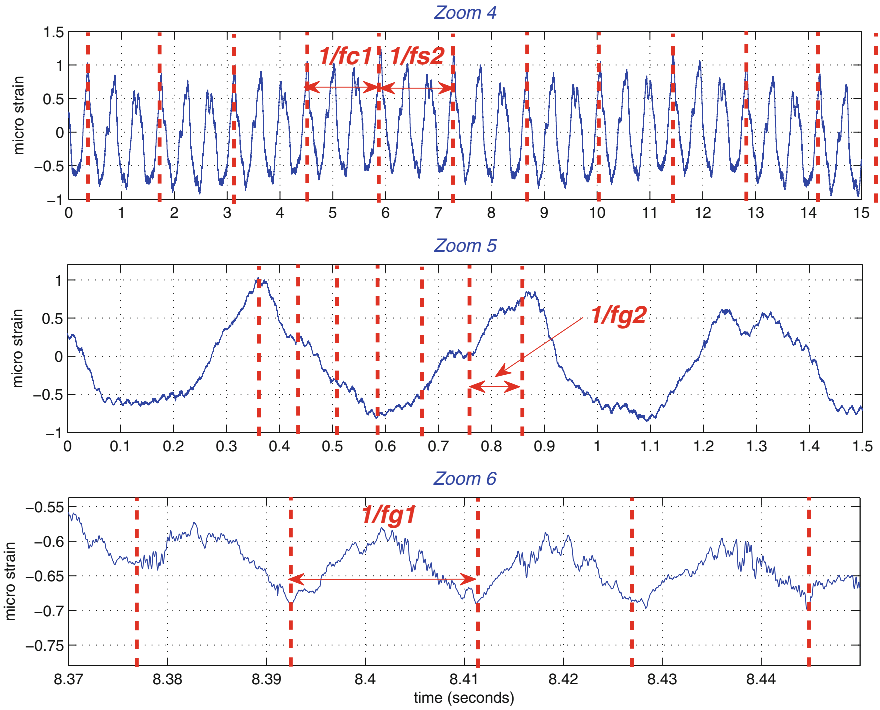


**Fig. 4.** Second three zoom sections

## 4 Conclusion

In this work, experimental measurement was done on a real industrial gearbox which is mounted on test rig. Strains of the housing surface of the ring gear were measured to identify characteristic frequencies of the PG in order to investigate its dynamic behaviour. The time signal collected using the piezoelectric strain sensor has a high SNR and an excellent reproducibility of periodic component of the signal especially in lower frequencies. In the way of future research, a supplementary analysis will be focused on the detection of gear faults using time signal acquired by using a strain gauge in order to investigate the capability of this sensor in damage cases.

**Acknowledgement.** This work is partially supported by NATIONAL SCHOOL OF ENGINEERS OF SFAX (ENIS)/Laboratory of Mechanics, Modelling and Production (LA2MP) and The National Centre of Research and Development (NCRD) in Poland under the research project no. PBS3/B6/21/2015.

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