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Study of the turbocharger shaft motion by means of infrared sensors

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ABSTRACT

This work describes a technique for measuring the precession movement of the shaft of small automotive turbochargers. The main novelty is that the technique is based on infrared light diode sensors. With presented technique it is possible to perform secure mounting of electronics and also to measure, with good accuracy, far enough from the turbocharger shaft. Both advantages allow applying it even in critical lubrication conditions and when blade contact occurs. The technique's main difficulties arise from the small size of the turbocharger shaft and the high precession movement in critical conditions. In order to generate the optimum albedo reflection for infrared measurement, a special cylindrical nut with larger diameter than the original one is assembled at the shaft tip in the compressor side. Following, shaft balancing, the calibration of the sensors and the compensation of errors from different sources are needed steps before the method is able to identify the main frequencies of shaft motion. Once synchronous and sub-synchronous frequencies have been obtained it is possible to reconstruct the instantaneous position of the shaft to determine its precession movement.

1. Introduction

The trend of internal combustion engines (ICE) is to improve efficiency, to fulfill the anti-pollution regulations, which are becoming more restrictive, and to maintain a power output that meets current user demand [1]. In this context, there are several studies and new technological proposals [2–5]. However, the most successful technique because of its “easy matching” and “noninvasive coupling” is boosting with turbochargers [6–8] thus complying with trends mentioned above.

The efficiency and proper performance of a turbocharger can be affected by several external causes. Some of these causes have been studied experimentally such as foreign objects entering the compressor [9], cuts in lubrication [10], mechanical friction losses [11]. Moreover, there are different models that helped to know different aspects of the turbocharger performance: vibrations models [12] [13], numerical models of the air flowing through the volute [14] and models to control the turbocharger flow [15].

An important variable that affects the turbocharger behavior is the precession movement of the shaft. It is a complex phenomenon which depends on effects such as:

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1.1. Hydrodynamic lubrication of the bearings

Most turbochargers use floating and semi-floating bearings, in both cases, there is a phenomenon called oil whirl/whip, which is based on the self-excited vibrations caused by the lubrication film [16].

1.2. Rotating shaft modes

They depend directly on the shaft speed and its deformation, and they include conical, translational, torsional and bending deformations [17] and each of these can spin into a forward (FW) or a backward (BW) movement.

1.3. Imbalances

Small turbochargers can spin at high speeds (230 krpm or more) and a small imbalance can produce large vibrations [18,19].

Different techniques have been developed to measure the shaft movement, such as inductive sensors [20], laser Doppler vibrometers [21], laser Doppler distance sensors [22] and photo sensing resistor [23], these three last techniques have been applied in larger shafts, which is not the case in present work. In small turbochargers with smaller shafts and high turbo speeds only inductive sensors [20] have been reported in the literature.

The assembly in the three previous cases is much more complex than the system described in this paper. In these three cases, optical access is required through the turbocharger bearing housing and the sensors are installed outside of the turbocharger and the accuracy of the measured will be affected by the relative movements between the turbocharger and the sensors (vibration). While, in the technique described in this article, the sensors can be installed directly in the compressor case inlet, pointing to the edge of the shaft. This is a great advantage in passenger car turbochargers as they are very compact and they present a complex access to the shaft. A further disadvantage of the above three cases is that the electronics are attached to the sensor and usually the electronics does not support extreme temperatures, making it difficult to test the turbocharger at very high or very low temperatures.

On the other hand, the main advantage of the described technique with respect the inductive sensors is that the infrared light diode sensors can be installed at distances higher than 2 mm from the shaft of the turbocharger and they present a good accuracy. It is an ideal characteristic for measuring during destructive tests.

In the present paper the precession movement is studied by means of optical infrared sensors. The infrared sensors have been applied in the measurement of the shaft motion and position of blades in large shafts [24–26]; however there are no previous works covering the use of this type of sensors for the measurement of the precession movement in small size turbochargers, as those used for ICE boosting.

To perform this technique, a cylindrical nut on the shaft tip at compressor side was installed. This cylindrical nut was used such as the objective of the positions sensors, to have an area big enough to reflect the infrared light.

In order to simplify the analysis of the results of this article, the deformations of the shaft will not be considered, because measuring these deformations requires measurements in different points along the shaft and only measurements in the shaft tip have been performed. Therefore, the present work is limited to measure rotational orbits described by the tip of the shaft.

The paper is structured as follows: Section 2 presents the experimental layout and the technique for sensors calibration; Section 3 presents the proposed measurement methodology, with details on procedure and data processing approach; Section 4 presents an application example, where the described methodology is used for studying the acceleration of a turbocharger during a turbocharged ICE tip in. Finally, conclusions are presented in Section 5.

2. Test bench layout and sensor calibration

In order to measure the position of the shaft, two infrared light diode sensors have been placed in a radial position at the compressor side (hereinafter sensors 1 2), pointing to the tip of the shaft and forming together an angle of 90°. The measuring chain is composed by a flexible optical fiber, an electronic amplifier (the characteristics of these sensors are in Table 1) and a Yokogawa digital scope with 16 channels and a maximum range of 10 Ms/s. To minimize the opening of the light beam after reflection, a cylindrical nut of Titanium with a large diameter of about 12 mm is placed in the tip of the compressor shaft. Furthermore the surface of this cylinder has been painted with a matte white color to get an albedo that maximizes the reflection of infrared light, with the objective of increasing the sensitivity of the sensors. Fig. 1 shows a scheme of the described system.

The sensors used are placed with a 3 mm gap, approximately, between the tip of the sensor and the surface of the cylindrical nut assembled to the shaft (Fig. 1). These sensors have operative ranges between 0.5 mm and 10 mm and are able to record data at frequencies up to 1 MHz. However, to avoid memory problems in the recording of the data, the acquisition frequency was set to a high enough frequency of 100 kHz.

The calibration curves of the sensors are determined using a positioning table and a micrometer. This device allows moving the sensor radially to the axis of the modified turbocharger shaft. Thus, the sensor can be positioned at different distances from the cylindrical nut, in order to determine the ratio between the voltage obtained by the electronic device of the sensor and the distance from the tip of the sensor to the surface of the cylindrical nut. This calibration arrangement has been also used to estimate the sensibility of the sensors. Fig. 2 shows the result of such sensibility study for distances around to 3 ± 0.5 mm, which is range of distance at which they are placed during the experiments. The curves of the two sensors

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