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Instantaneous Angular Speed (IAS) signal for abnormal combustion diagnosis in an I.C. engine

Mohamadjavad Ghoudjani [a], **Farzad Rafieian** [a,*], **Abolfazl Mohammadebrahim** [a], **Hassan Jalali** [b]

[a] *Department of Mechanical Engineering, Arak University of Technology, Arak, 3818146763, IRAN*

[b] *Mechanical and Construction Engineering Department, Northumbria University, Newcastle Upon Tyne, UK*

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ABSTRACT

This paper is about the application of instantaneous angular speed (IAS) signal in a 3-liter six-cylinder gasoline engine. The study is in continuation of former work in which a measurement system was developed for this signal on a rotating machine. The future trend of the research is to measure IAS in an I.C. engine. Therefore, the objective of the current work is to provide a verified software tool which can run simulated experiments with IAS signal output under healthy/faulty conditions. An engine model with detailed crankshaft elements is established in the GT-SUITE[*] software. Under the GT-SUITE environment, IAS signal output is obtained through simulated experiments. In order to validate the tool, the first torsional natural frequency of the crankshaft obtained from frequency analysis on the IAS signal is compared with the result of modal analysis on the crankshaft structure using the F.E. method. Also, the value is compared with the prediction from the GT CrankAnalysis module. A good match is found, which shows the validity of the developed software tool. Faulty condition of misfiring in one cylinder is simulated using this tool, and expected observations on the IAS output signal are verified to address the future trend of the research using the developed tool in this study.

[*] Corresponding author. Cell.: +98 913 114 2655;
E-mail address(es): farzad.rafieian@gmail.com (F. Rafieian)

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[*] Gamma Technologies

1) Introduction

During the past 25 years, many researchers have used the Instantaneous Angular Speed (IAS) signal for various purposes in rotating machinery diagnosis [1]. Easy installation, needless for regular calibration, and cost-effective usage are the main advantages of the suggested methods [2]. Furthermore, angular speed is usually the closest parameter to the discrete mechanical event under consideration. For IAS measurement, the elastic torsional waves in the rotor are recorded by an encoder device installed directly on the rotor shaft. This is unlike the detection of lateral vibrations, where the causing elastic waves need to pass through several contact interfaces before they reach the sensing device. The usage of the information contained in IAS fluctuations has thus been continuously extended into various fields such as designing a feed system for TIG welding process [3], characterization of the material removal regime in robotic grinding [4], detecting tool wear in milling [5], predicting rotor bar failure in squirrel-cage motors [6] and condition monitoring of wind turbine gearboxes [7].

A recent but rich field to employ the IAS signal for diagnostic purposes is internal combustion engines (ICEs). ICEs play an irreplaceable role in the present industry world, including train, marine, or power generation units. An example of a common fault in diesel engines is misfiring, which may stem from a variety of reasons. An intense change in the driving environment or malfunction of the fuel injection system are the primary reasons for abnormal combustion in these engines [8]. Hence ensuring reliability over their service life is of great importance. The use of in-cylinder pressure sensors has been the most common approach to monitor their performance. However, this technique is no longer effective due to its intrusive nature and the exorbitant price of the sensors [9]. The repair process of these sensors is also time-consuming and requires long downtimes of the system leading to productivity loss. Instead, experimental investigations about using the IAS signal for diagnosing misfire events in large diesel engines are reported [10,11]. In a power train composed of a diesel engine, a flexible coupling, and a dynamometer, the coupling is identified as the best location for measuring torsional vibrations of the crankshaft for abnormal combustion diagnosis [12]. This has further progressed into automated levels using an enormous number of simulation data and employing Artificial Neural Network (ANN) to diagnose faults instantly [13]. Surprisingly, the continual improvement of commercial vehicles to meet fuel emission standards has led to cylinder deactivation (CDA) techniques for power optimization and managing exhaust temperature which raises concerns about the engine torsional vibrations to be measured and considered in the design process [14,15].

This paper is organized as follows. The process of software modeling for a 6-cylinder engine is described in Section 2. This includes modeling the engine process and its IAS output in the GT-SUITE software. The crankshaft structure is also modeled in the ANSYS software. Torsional vibration characteristics of the engine predicted by the two independent software models are verified with one another as reported in Section 3. The effect of some imposed misfiring events on the engine is also demonstrated by the software tools to conclude their capability for future work.

1.1) Former work and setup

The current paper presents the research conducted in continuation of former work, which initiated a test rig for measuring the IAS on a bench grinder's rotor shown in Fig. 1 [16]. The data acquisition system could well capture the torsional vibration characteristics of the shaft used for modeling and grinding force identification. The future trend of the ongoing research is to extend this measurement system for an I.C engine in order to investigate common faults such as misfiring. The current work paves this way by providing validated software tools needed to simulate the IAS signal output from the engine and the effects of common faults on IAS fluctuations. IAS is a fairly new signal used for experimental vibration analysis internationally. To the authors' knowledge, no published or applied work with this signal is found in Iran. The main contribution of the current work is providing the requirements for field application of the IAS DAQ system on an I.C. engine.

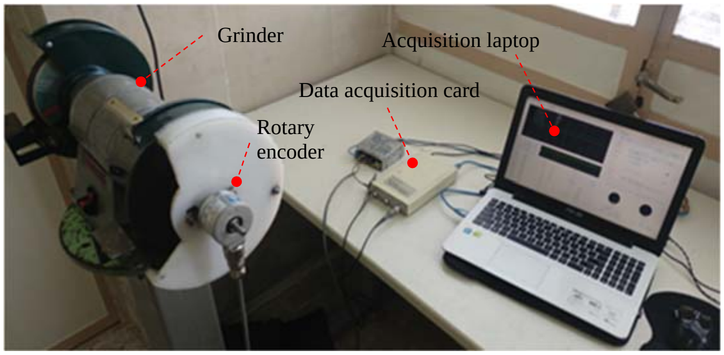


Figure 1: IAS measurement setup

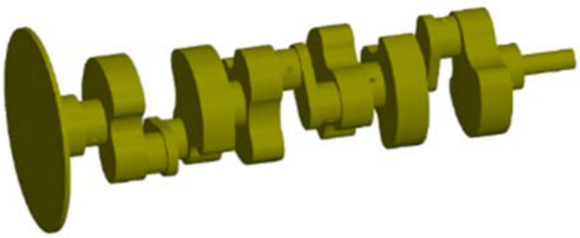
2) Modeling and simulation

Details of the software tool generated for this work are presented in this section. The engine model, including the crankshaft structure and other related objects, is created in the GT-SUITE platform. GT-SUITE uses a library for modeling fluid flow, thermal, mechanical, electrical, magnetic, chemistry, and control aspects of an engine. This tool can then give the torsional vibration characteristics of the crankshaft. It can also simulate any desired working condition of the engine, healthy or faulty while giving the IAS output signal. The crankshaft is also modeled by the finite element method using the ANSYS software in order to verify the model from GT-SUITE regarding the predicted torsional vibration characteristics.

2.1) Crankshaft discretization

The 3-D crankshaft model and its dimensions for the engine used in this work are illustrated in Fig. 2. The model is then imported into the GEM3D environment and discretized in order to transform it into geometric objects. The object is automatically parameterized by the software, and parametric values such as stiffness coefficient, damping coefficient and moment of inertia are estimated for parts. The discretized crankshaft is shown in Fig. 3. Each part of the crankshaft will then have a separate label in the software. The model is now ready to be imported into the GT-ISE† environment in order to build up a process model for the whole engine.

† Integrated Simulation Environment



Parameter	**Value** (mm)
Crankshaft length	510.3
Journal diameter	45
Main journals distance	132
Crankpin diameter	40
Journal to crankpin distance	51
Crank radius	37.59

Figure 2: CAD model of the crankshaft and dimensions

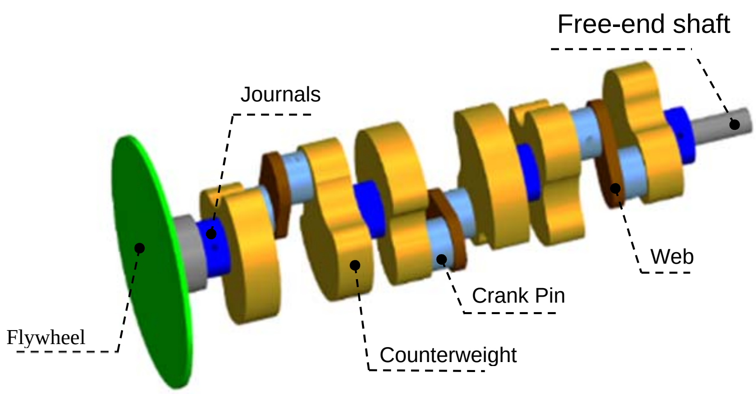


Figure 3: Discretized crankshaft

2.2) Engine model in GT-ISE

A schematic view of the engine model in the GT-ISE environment is shown in Fig. 4. In this environment, a template is assigned to each object to be filled with its required parameters, and objects are connected automatically. Torsional frequency analysis in GT-ISE is activated to output torsional natural frequencies of the crankshaft for comparison with the results of analysis by ANSYS reported later. Other engine characteristics, such as firing order and firing interval, are defined via the Crank Analysis feature of the software. The general specification of the engine is shown in Table1.

Table 1: Engine properties

Engine model	Lambda II Mpi
Engine type	4-stroke
Capacity (L)	3
Bore × Stroke (mm)	92 × 75.2
Rated power (kw)/rpm	184/6400
Rated torque (Nm)/rpm	282/5000
Compression ratio	10.4:1
Analysis type	Torsional
Firing order	1-5-3-6-2-4
Firing interval (deg)	120
Simulation	Constant speed
Speed (rpm)	1500

2.3) Simulation of misfire

Misfire occurs for various reasons, such as malfunctioning the fuel injection system or extreme driving environment change [8]. In the simulated experiment presented in this work, misfire is imposed once in only one cylinder (cylinder 4) and once in three cylinders (cylinders 3, 2, and 4) by disabling the fuel injection system. In other words, the simulation is set such that no fuel is

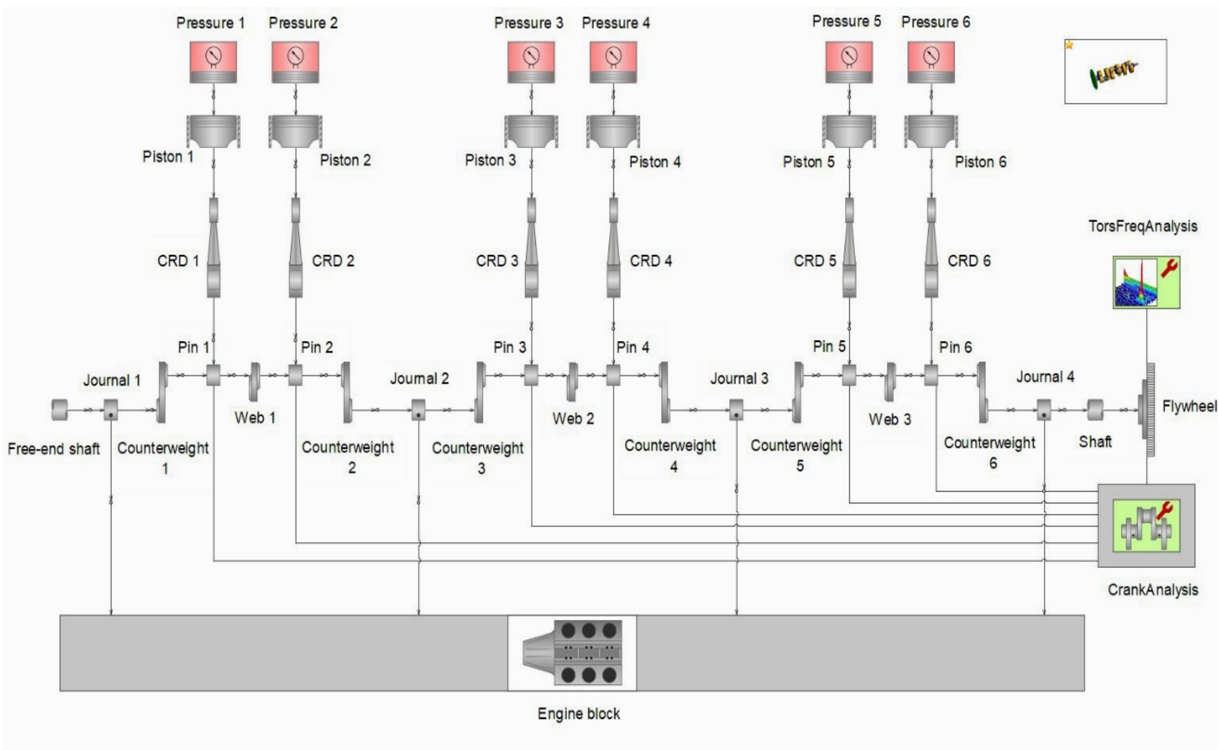


Figure 4: Generated GT-ISE model of the crankshaft

injected into the cylinder, and thus, the in-cylinder pressure for this case results only from the piston compression. However, given the pressure generated by piston compression is relatively low compared to when the combustion process happens in normal conditions, the in-cylinder pressure of cylinder four is set to zero for this simulated experiment. The cylinders' pressure profile operating under normal conditions is depicted in Fig. 5.

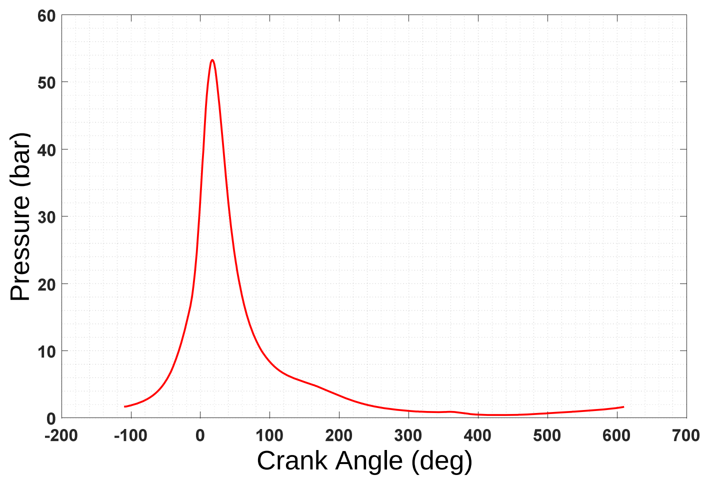


Figure 5: In-cylinder pressure profile under normal condition

The engine model created in GT-SUITE software, as explained through Sections 2.1 to 2.3 is capable of predicting the torsional natural frequencies of the crankshaft as well as generating the IAS signal output from it under normal and faulty (misfire) conditions.

2.4) Finite element model of crankshaft

The six-cylinder crankshaft CAD model was imported next into the ANSYS software for modal analysis. The objective was to obtain the crankshaft's first torsional vibration mode shape and natural frequency. The generated mesh and material properties used in this analysis are shown in Fig. 6 and Table 2. Cylindrical support type is considered for the position of four journal bearings where the crankshaft is fixed to the engine block, as shown in Fig. 7. This support type imposes fixed radial and axial constraints, but tangential movements for the shaft are allowed. The total number of 954130 TET10 elements (10 nodes tetrahedral) were used for creating the mesh on the crankshaft. A maximum number of 8 modes were set to be extracted by the modal solver in ANSYS.

Table 2: Structural steel properties used for FE analysis in ANSYS

No.	Property	Value
1	Density	7850 (Kg/m^3)
2	Young's modulus	2e+11 (c)
3	Poisson's ratio	0.3
4	Shear modulus	7.692e+10 (Pa)
5	Bulk modulus	1.66e+11 (Pa)
6	Thermal expansion coefficient	1.2e-5 $(1/°C)$

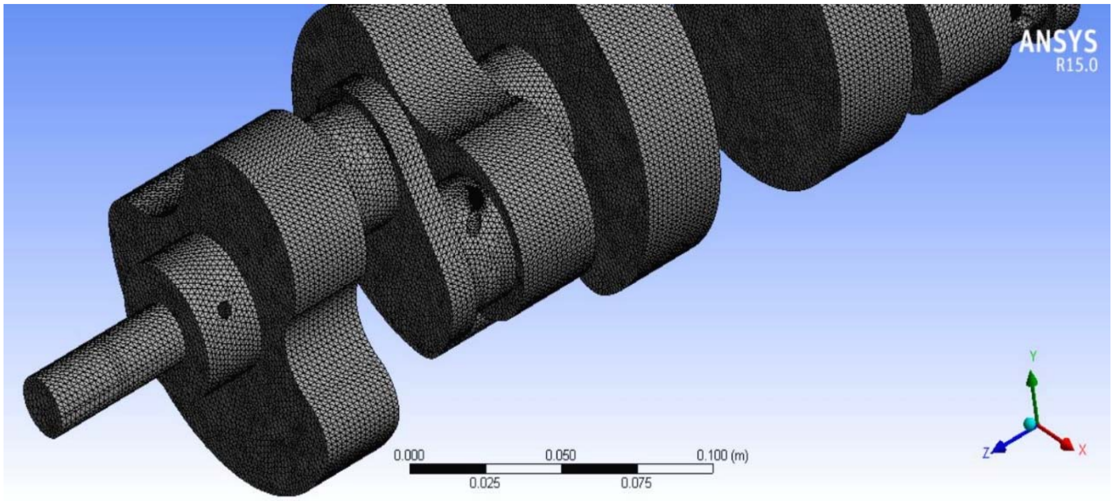


Figure 6: Generated mesh for FE analysis of crankshaft in the ANSYS software

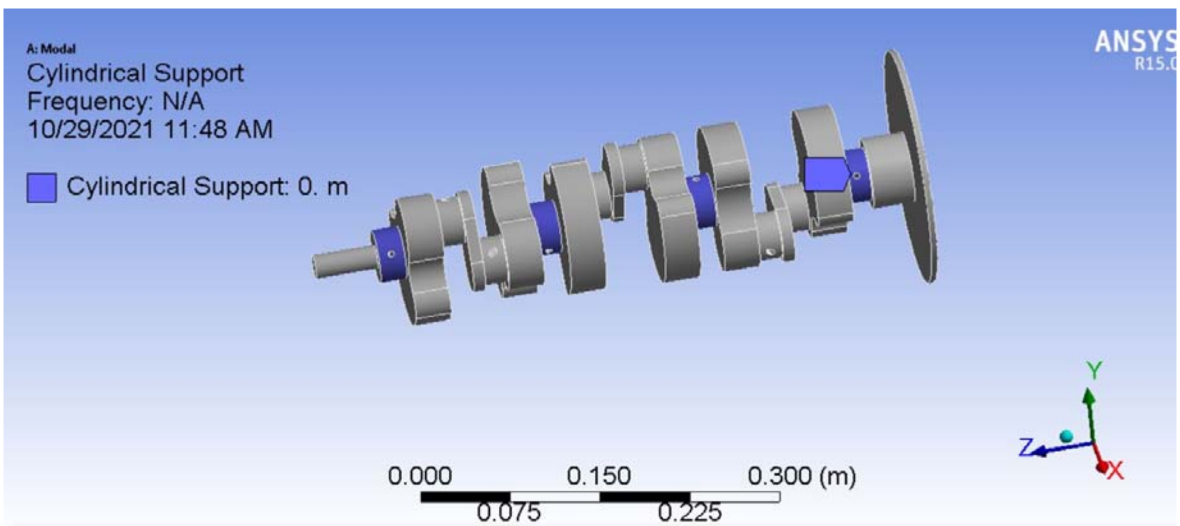


Figure 7: Cylindrical supports for journal bearings' positions on the crankshaft

3) Results and discussion

In this section, the developed software tool for the engine is verified. This tool will be employed in the future trend of the research to investigate the effects of various faults on the output IAS signal. It is thus crucial to verify if fundamental engine characteristics and vibrational behaviors are observed using simulated experiments with such a tool.

3.1) Torsional natural frequency

The fundamental vibrational characteristic of the engine under study is the crankshaft's first torsional natural frequency. This value is obtained with three approaches to be compared and thus verify the developed software tools.

First, from the 8 vibration modes of the crankshaft predicted by modal analysis using ANSYS, the one with pure torsional deflections is selected as the first torsional mode with the shape and frequency of 721.5 Hz reported in Fig. 8.

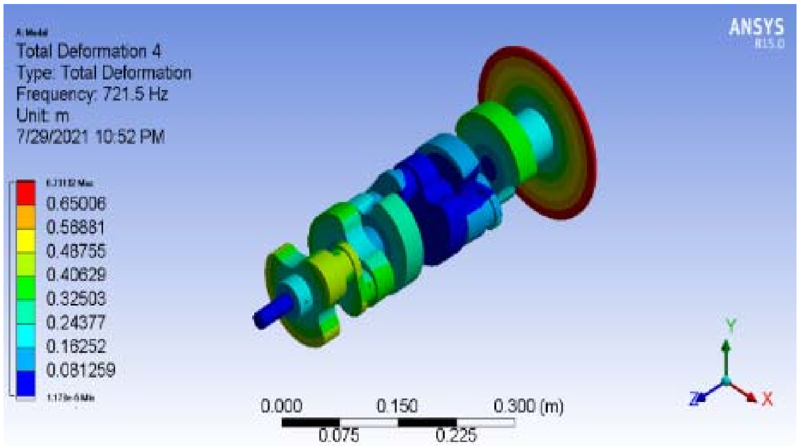
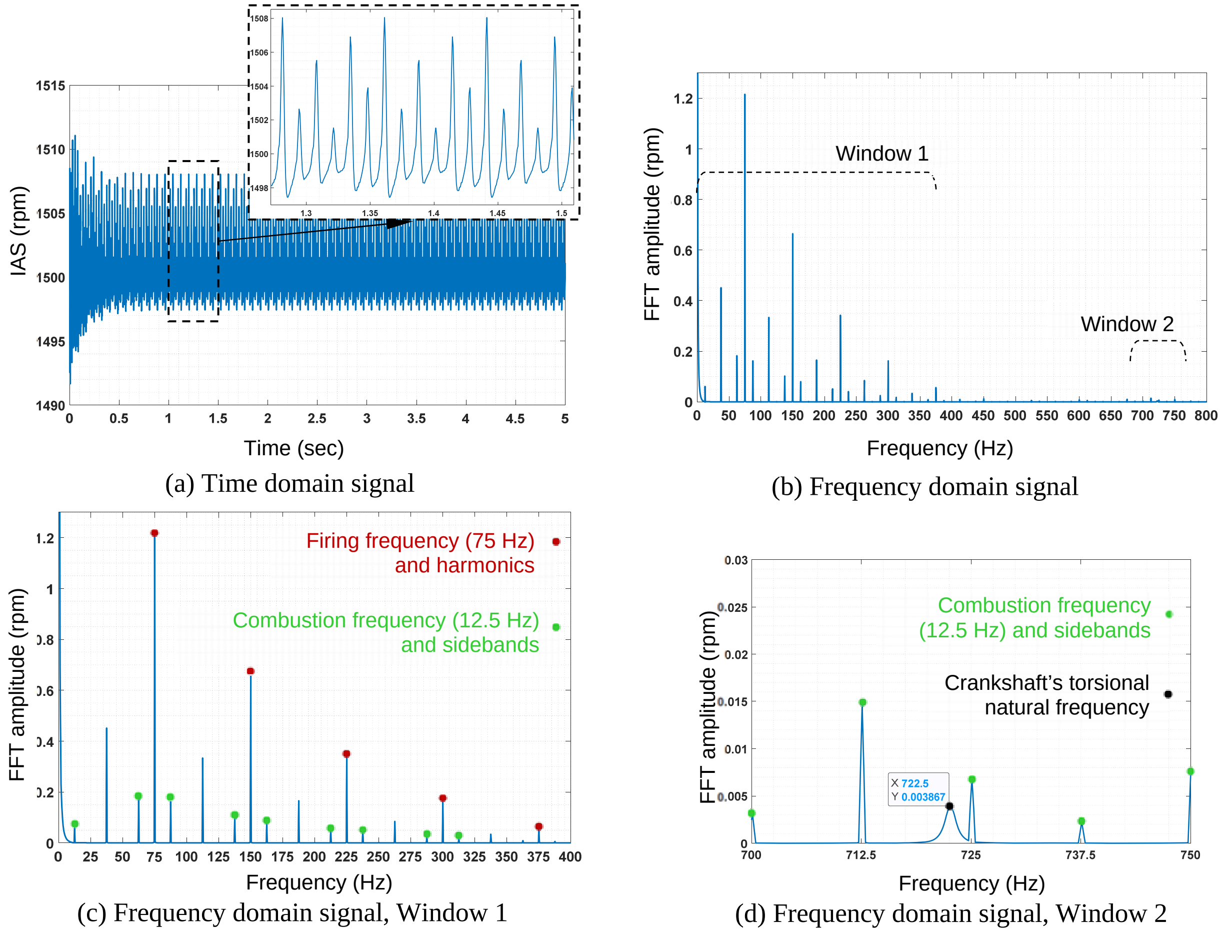


Figure 8: First torsional vibration mode from modal analysis using ANSYS

The second approach is using the IAS signal output from the engine model at the free-end shaft object in the GT-SUITE environment. A simulated experiment is run from the engine under normal conditions, and the output IAS signal is obtained (See Fig. 9a). The time-domain signal is then transformed into the frequency domain, as shown in Fig. 9b, where a sound peak at 722.5 Hz becomes evident for the torsional natural frequency of the rotating assembly (See Fig. 9d). Other frequency contents demonstrated in Fig. 9b-d are investigated to check if expected behaviors from the engine are properly reflected into the output IAS signal. The firing frequency for the engine understudy is calculated as follows [14]:

$$f_e = N \times \frac{1\ min}{60\ sec} \times O_d \tag{1}$$

in where f_e is the engine firing frequency, N is the angular speed in rpm and O_d is the dominant order of torsional vibrations, which equals half of the number of active cylinders. With $N = 1500$ and $O_d = 3$ for the case under study, the firing frequency will be 75 Hz. The firing frequency and its harmonics are thus evidently visible in Fig. 9c. Also, the combustion cycle frequency of 12.5 Hz (which if half of the rotational frequency) is clearly visible as a separate peak as well as sidebands around the harmonics of the firing frequency.



(a) Time domain signal

(b) Frequency domain signal

(c) Frequency domain signal, Window 1

(d) Frequency domain signal, Window 2

Figure 9: IAS signal output under normal conditions

The third prediction of torsional natural frequency is made by the GT-SUITE software. The torsional frequency analysis module of the software calculated 21 torsional mode shapes of the crankshaft, with the first one at 723.4 Hz.

The comparison between the three approaches is summarized in Table 3. Predictions differ by a maximum of 0.26 percent, which is considered a perfect match indicating the validity of the developed software tool.

Table 3: Obtained torsional natural frequency

Approach	Determined frequency
Modal analysis in ANSYS	721.5 Hz
GT-ISE estimation (Crankshaft’s first torsional natural frequency)	723.4 Hz
FFT of output IAS signal	722.5 Hz

3.2) Misfiring event

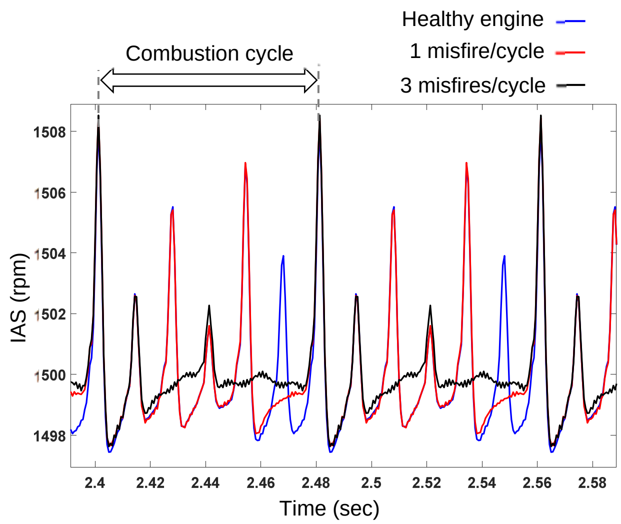
In this last section, the developed software tool is employed to demonstrate the effect of faulty conditions on the output IAS signal. The expected observations are discussed, and the future trend of the work is addressed.

The misfiring fault, as explained in section 2.3, is imposed on the engine model. A fundamental equation of the torque balance for an engine with a rigid crankshaft is [13]:

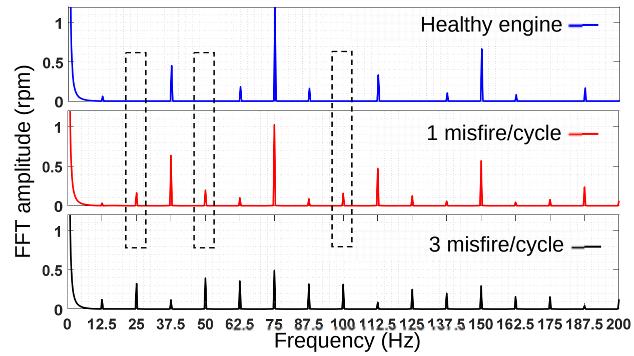
$$I(\theta) \cdot \ddot{\theta} + \frac{1}{2} \cdot \frac{\partial I(\theta)}{\partial \theta} \cdot \dot{\theta}^2 = T_g + T_{fric} + T_{load} \qquad (2)$$

where $I(\theta)$ is the crankshaft’s polar moment of inertia, θ is the crank angle, T_g is the torque caused by combustion, T_{fric} is the friction torque and T_{load} is the external torque. Misfiring contributes to the combustion torque T_g magnitude and frequency contents. The fundamental frequency of T_g is the combustion cycle frequency which is half of the engine’s rotational frequency; 12.5 Hz for the case under study. Misfires repeat on this cyclic base but may have multiple occurrences based on the number of faulty cylinders involved. For the demonstration of this work, a simulated experiment with one misfire event per combustion cycle is run first. Another simulation with three misfire events per combustion cycle is run as well. The output IAS signals from the healthy engine and the two faulty cases are shown in Fig. 10a. The signals are transformed into the frequency domain as shown in Fig. 10b. Multiples of the combustion cycle frequency which are not present in the healthy case IAS output, appear in the faulty cases. This plausible observation confirms one more time the validity of the developed software tool.

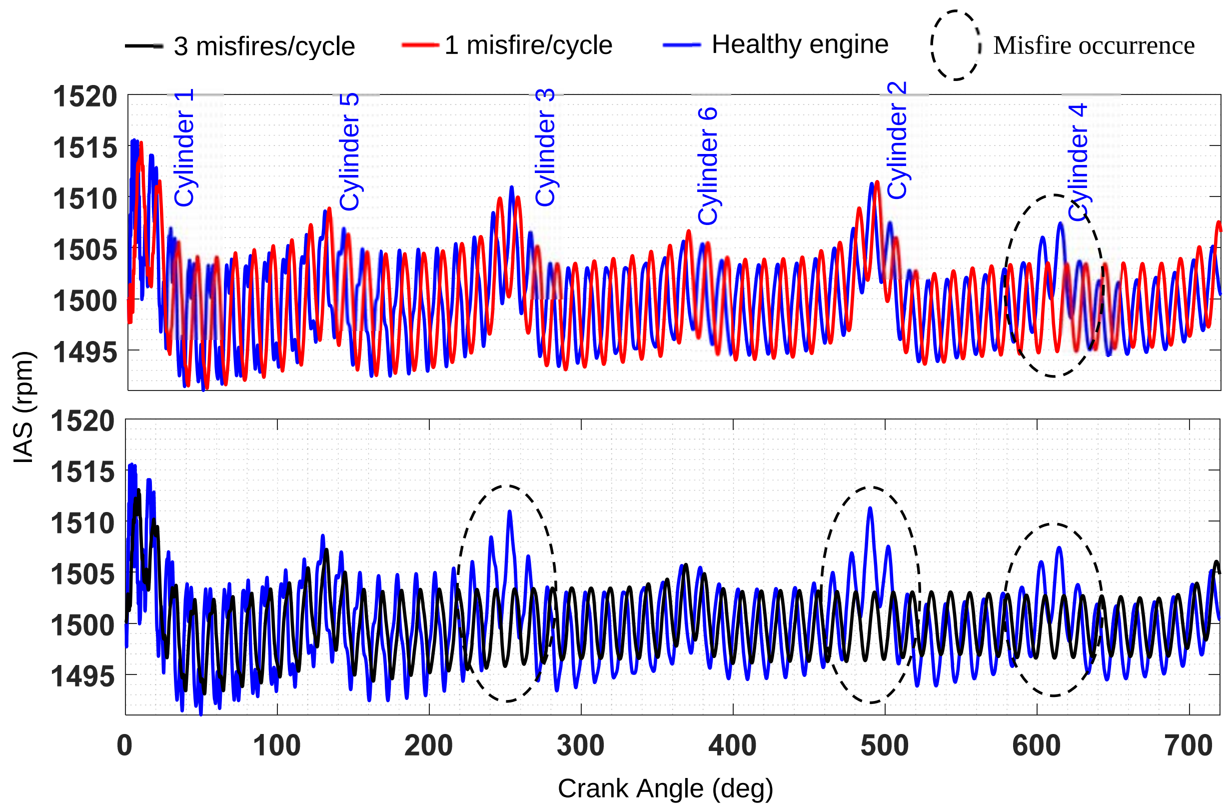
However, the frequency domain representations of the IAS signal for the two faulty cases shown in Fig. 10b reveals no clear distinction between these cases. That is due to the fact that vibration components at the multiples of combustion cycle frequency (multiples of 12.5 Hz) exist in both cases, with amplifications in one and attenuations in others. Therefore, these components cannot



(a) Time domain IAS signals



(b) Frequency domain IAS signals



(c) Angle domain IAS signals with missing peaks as indicators of misfire occurrences

Figure 10: IAS signal output under faulty conditions

be distinguished for the diagnosis of faulty cylinders. One further capability of the IAS measurement system becomes useful under such conditions. Samples of the IAS signal are acquired at angular increments rather than at constant intervals of time.

In conventional measurement systems, samples of data are acquired based on the sampling frequency F_s set on the DAQ system. The system then uses its internal clock to trigger measurements at every interval of $\Delta t = 1/F_s$ seconds. Triggering is thus regardless of any mechanical event in the machine, and two numerical values (time and the measured parameter; angular speed in this work) are recorded. Now consider if another piece of information - crank angle - is added to each record. In case each data sample is associated with a crank angle during rotation, it becomes possible to make correlations between sections of the signal and the rotating parts or events under consideration to diagnose faults. For the angle domain representation in Fig. 10c, this is simply a software output versus angle rather than time. However, in the real DAQ system developed, this is accomplished through triggering the data acquisition card by an encoder signal of 1024 pulses per revolution. Therefore, the IAS signals can be represented in the angle domain similar to Fig. 10c. From such representation, it is evidently possible to locate the faulty cylinders. Transformation of such signal into the frequency domain will be even more useful. Vibrations components will be demonstrated versus angular frequency rather than events per second (or Hz). That means the unit for the abscissa axis will be the number of events per revolution. In such representation, the two faulty cases of one misfire per engine cycle and three misfires per engine cycle will have distinct frequencies. The two cases are selected only as a demonstrative example of the capabilities of the IAS measurement system. It is shown that one cannot distinguish them from the conventional frequency spectrum (Fig. 10b). However, they are clearly visible and distinct in the angle domain plot of Fig. 10c. In this figure, misfire occurrences are identified at the angular positions within a cycle where a missing peak is observed as compared to the healthy signal in blue. Therefore, a frequency spectrum in this domain may also help for the distinction between the two faulty cases. Future works will address practical examples for this purpose and elaborate on the angular domain features of the IAS signal in an I.C. engine. The validated engine model created under the GT-SUITE software will be used to run simulations giving the desired outputs such as the IAS signal. This will be resembling actual experiments prior to the application of the DAQ system on an IC engine.

4) Conclusion

This paper investigated the application of crankshaft’s instantaneous angular speed (IAS) signal, or say torsional vibrations, for fault diagnosis in I.C. engines. The research is conducted to continue former efforts to establish an IAS measurement system on a rotating machine. Given the future trend of the work to apply this measurement system on an I.C. engine, a validated software tool was needed to run simulated experiments to analyze the IAS signal before being acquired in practice. Using a sample crankshaft of a six-cylinder engine, a model was created in GT-SUITE software. The output IAS signal from the model was verified through frequency analysis of its components. The crankshaft’s torsional natural frequency obtained from this signal was compared to the modal analysis result with the FE method on the crankshaft’s structure. Also, expected components such as combustion cycle frequency and firing frequency were obtained from IAS frequency analysis. The validated model was then used to simulate healthy and faulty conditions of the engine to address the future trend of the ongoing research.

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