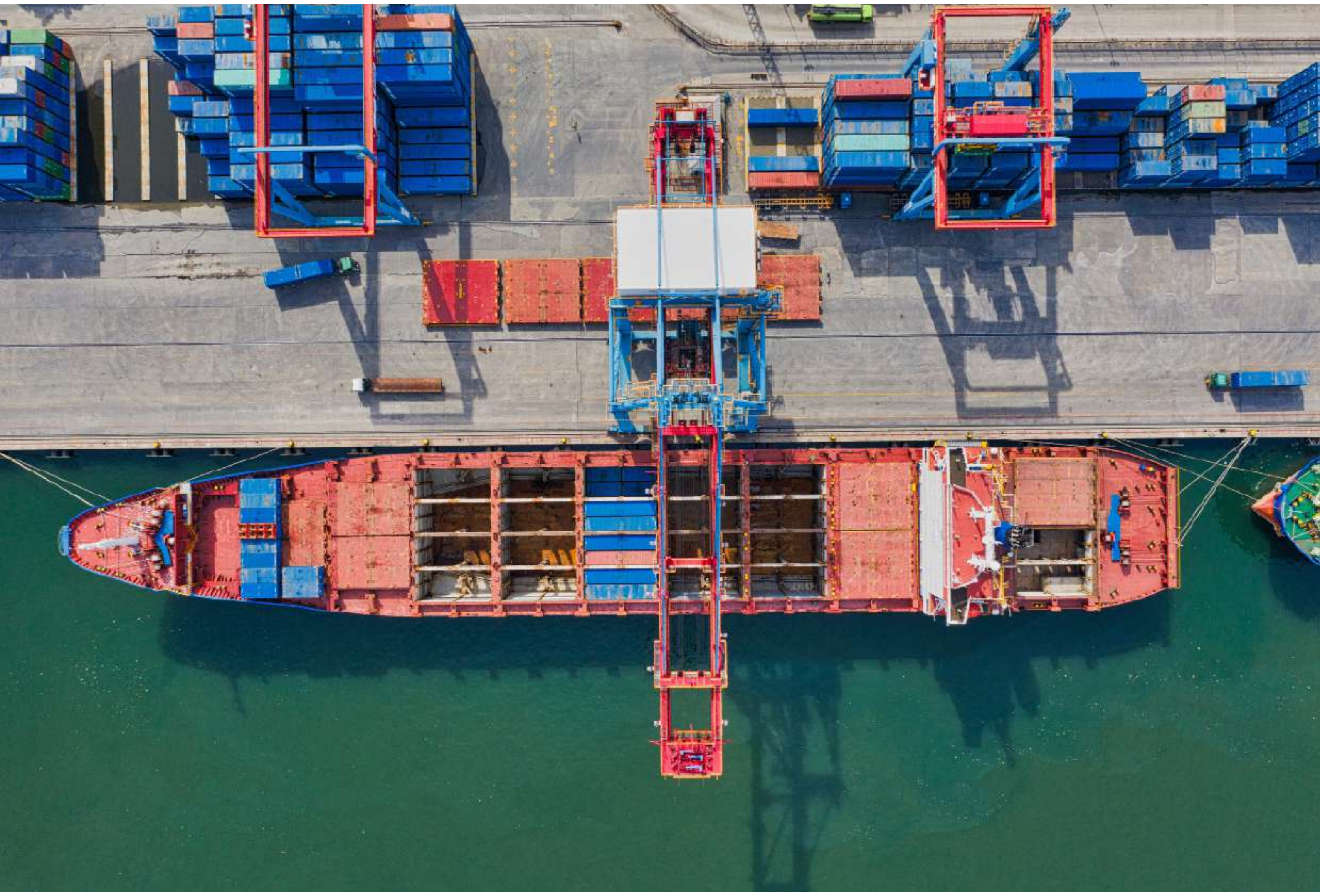
PATH TO INTELLIGENT ENGINE DIAGNOSTICS

Part 1: Crankshaft Dynamics

Whitepaper



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01

APPROACH TO SAVINGS

In light of the most recent push for green initiatives, as well as the international economy's volatility, a targeted bottom-up approach to savings is essential. Therefore, for large internal combustion power plants in the shipping and power generation industries, improved operational insight and management through condition based maintenance carries a substantial impact on fuel and maintenance savings, which result to optimised service intervals, reduced down time, and more efficient, compliant engines.

> *"Condition based maintenance carries a substantial impact on fuel and maintenance savings, which result to optimised service intervals, reduced down time, and more efficient, compliant engines."*

With the advent of digitalisation, a new frontier is created in improving the internal combustion engines' condition based maintenance, by gaining unprecedented access to high precision big data, and thus being able to implement intelligent data processing and engine modelling techniques to determine the degradation and even predict faults.

As a result, continuous monitoring of key engine parameters allows for the identification of the current engine condition, degradation trends, and perhaps most importantly, imminent engine failures.

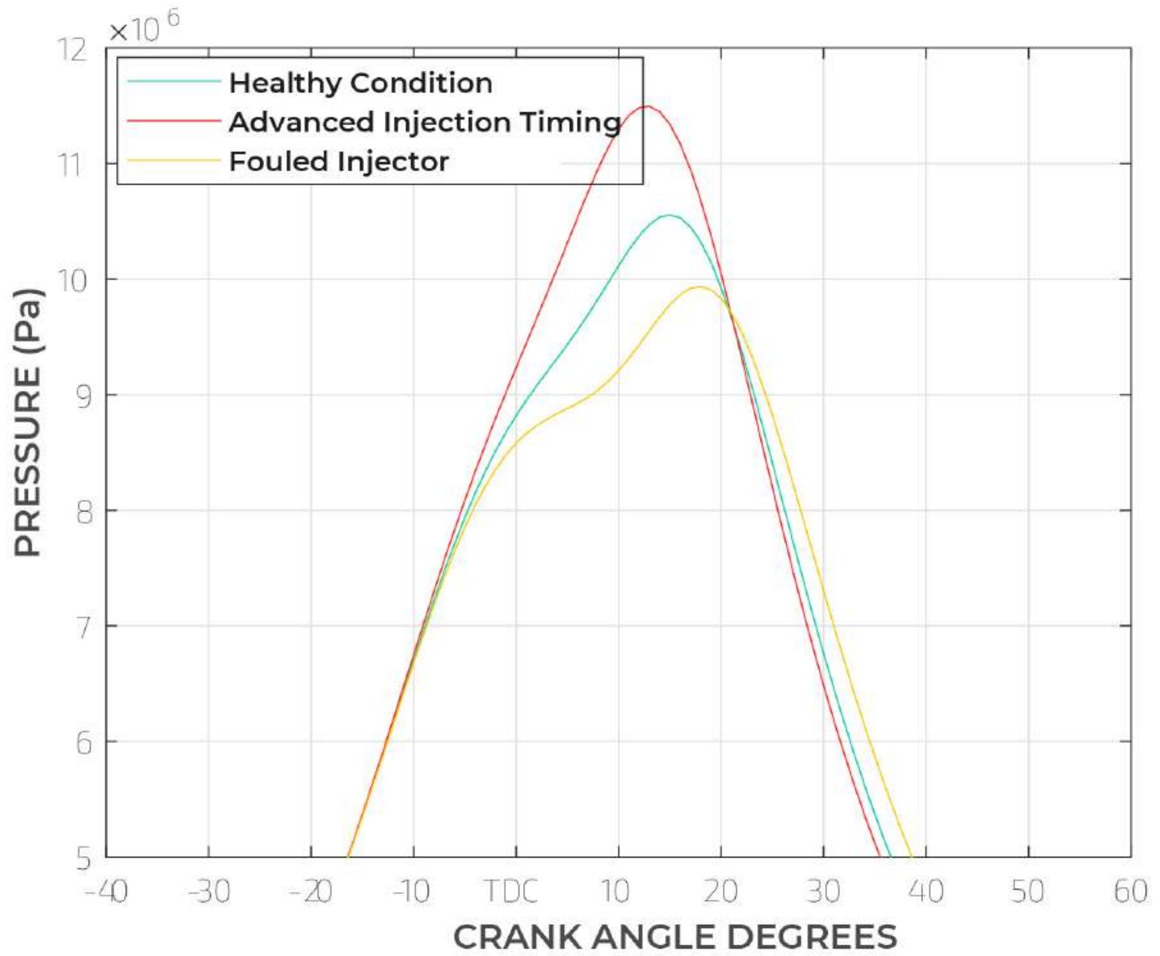
Consequently, on the path to intelligent engine diagnostics, the most important decision lies firstly with which parameters to monitor, and secondly with how to process these parameters to extract meaningful information.

02

VITAL MEASUREMENTS

Undoubtedly at the heart of every healthy egine lies a healthy in-cylinder pressure diagram. This parameter is so vital since it reveals information about injector condition, fuel quality, ignition timing, blow-by or engine valve leaks etc.

A few examples of which can be seen below:



In-cylinder pressure diagram at faulty vs healthy condition

Therefore, through the development of ever more robust pressure sensors, it is considered a requirement to obtain the in-cylinder pressure diagram at certain critical time intervals throughout the engine's lifecycle, such as before/after major overhauls, or during severe engine troubleshooting.

This might leave a large period where such critical information concerning the engine is absent, yet frequent (let alone continuous) measurements of the in-cylinder pressure diagrams can pose a considerable expense, due to the sensor costs, their prescribed shelf life, as well as the complex sensor network that has to be deployed for simultaneous monitoring on all cylinders.

AN IMPORTANT QUESTION IS POSED:

Which engine parameter can be obtained for continuous monitoring, yet also reveal critical information about the engine condition and performance?

THE ANSWER IS THE INSTANTANEOUS CRANKSHAFT TORQUE.

03

UNDERSTANDING CRANKSHAFT DYNAMICS

Measuring the intermediate shaft torque at low sample rates is certainly wide spread, with this data predominantly used for ascertaining the average power produced from a number of engine revolutions. This data is then commonly used in conjunction with Flow Meters to evaluate the Specific Fuel Oil Consumption (SFOC) and for plotting the engine power curves at various load levels in an array of different conditions. However, aided by advances in data storage and transmission, measuring the instantaneous crankshaft torque at high sample rates and high precision for such large applications is a relatively recent and non-intrusive measurement technique which can be of high value when practicing condition based maintenance.

> ***"Instantaneous crankshaft torque at high sample rates and high precision is a relatively recent and non-intrusive measurement technique. which can be of high value when practicing condition-based maintenance."***

Most importantly, the instantaneous crankshaft torque is a single measurement, which encapsulates simultaneously information regarding the combustion events in all engine cylinders for every instant. In other words, this measurement acts as a signature for each type of engine and its condition; i.e. its torque profile. Therefore, the first step in attempting to extract useful information from this measurement, is the determination of the relationship between the in-cylinder pressure and the instantaneous crankshaft torque, by understanding the crankshaft's dynamics.

It is intuitive to think that the output torque of the engine at any instant, is exactly equivalent to the sum of all torques from every cylinder at that instant. However, two additional phenomena significantly complicate the above, which include the variable inertia of the reciprocating parts attached to the crankshaft (e.g. connecting rods and pistons), and the crankshaft's torsional flexibility.

Subsequently, as one cylinder fires, the torque generated goes into accelerating the rotating and reciprocating masses of the crankshaft and piston assembly, deforming the crankshaft, overcoming the friction in the bearings, cylinders and chaindrive, and lastly to the engine load (e.g. generator, propeller, dynamometer, etc.) as seen below:

COMBUSTION TORQUE
Combustion gases generate torque in each cylinder

=

INERTIA TORQUE
Accelerating the rotating and reciprocating masses within engine

+

ENGINE FRICTION TORQUE
Torque required to overcome the friction of bearings, pistons, chaindrive, etc.

+

CRANKSHAFT DEFORMATION TORQUE
Torque transmitted and part of it dissipated through the deforming crankshaft

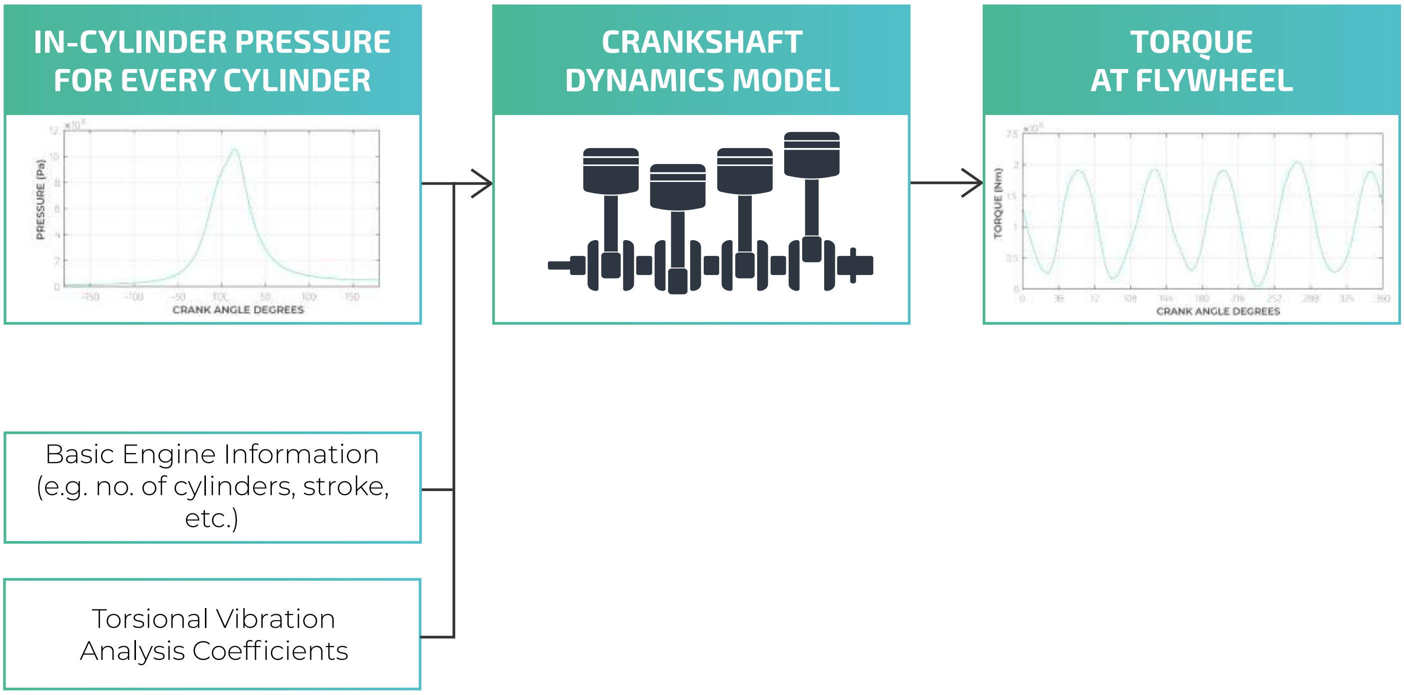
+

ENGINE LOAD TORQUE
Remaining torque goes into the engine load

Crankshaft torque balance

Similar to a person waving a rope, where the excitation they produce on the one end eventually reaches the other, the torque gets transmitted from the piston through the crankshaft, to the flywheel where the torque meter takes the measurement, and through the rest of the shafting system, to the engine's load.

With many cylinders firing at different instants, its equivalent to multiple people standing at regular distances along the rope and adding their own excitation component to it, where eventually what reaches the other end is a complex pattern of oscillations. The system of differential equations that describe this pattern are therefore used as the governing equations to the crankshaft dynamics model as shown below:



Crankshaft dynamics model inputs and outputs

04

OBTAINING CRITICAL INFORMATION

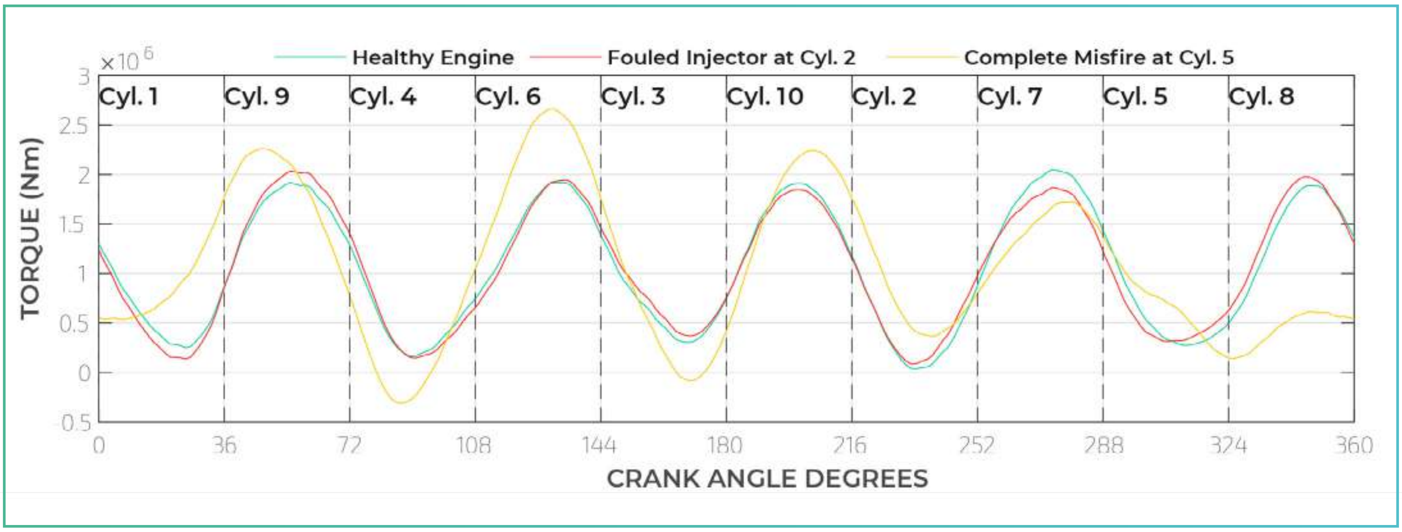
> *"A crankshaft dynamics model is a very useful tool to have as it can be further exploited in a number of ways, so as to provide critical information about the engine."*

A crankshaft dynamics model is a very useful tool to have as it can be further exploited in a number of ways, so as to provide critical information about the engine. Firstly, a baseline of a healthy instantaneous crankshaft torque signal is established. The baseline considers the torque signal at some reference engine conditions such as during engine shop tests or after major overhauls, which represents the engine's healthy state. Alternatively, if the instantaneous crankshaft torque signal is not available to establish the baseline, the in-cylinder pressure can be used which along with the crankshaft dynamics model, will predict the engine's torque signal for its healthy state.

Consequently, one can easily spot any deviations by comparing the healthy torque signal as obtained from the crankshaft dynamics model, to any other torque signal obtained from the engine.

Secondly, engine failure mapping is conducted on the instantaneous crankshaft torque signal. In other words, the effect of various types of failures on the engine's in-cylinder pressure is mostly generic and well documented in academic resources, as well as through the operator's records and experience. Hence, by employing the crankshaft dynamics model, the effect of such engine failures can now be observed or 'mapped' on the instantaneous crankshaft torque, as demonstrated on the next page.

This way a database of torque signals at unhealthy engine conditions can be compiled, and compared to the currently measured instantaneous crankshaft torque signal.

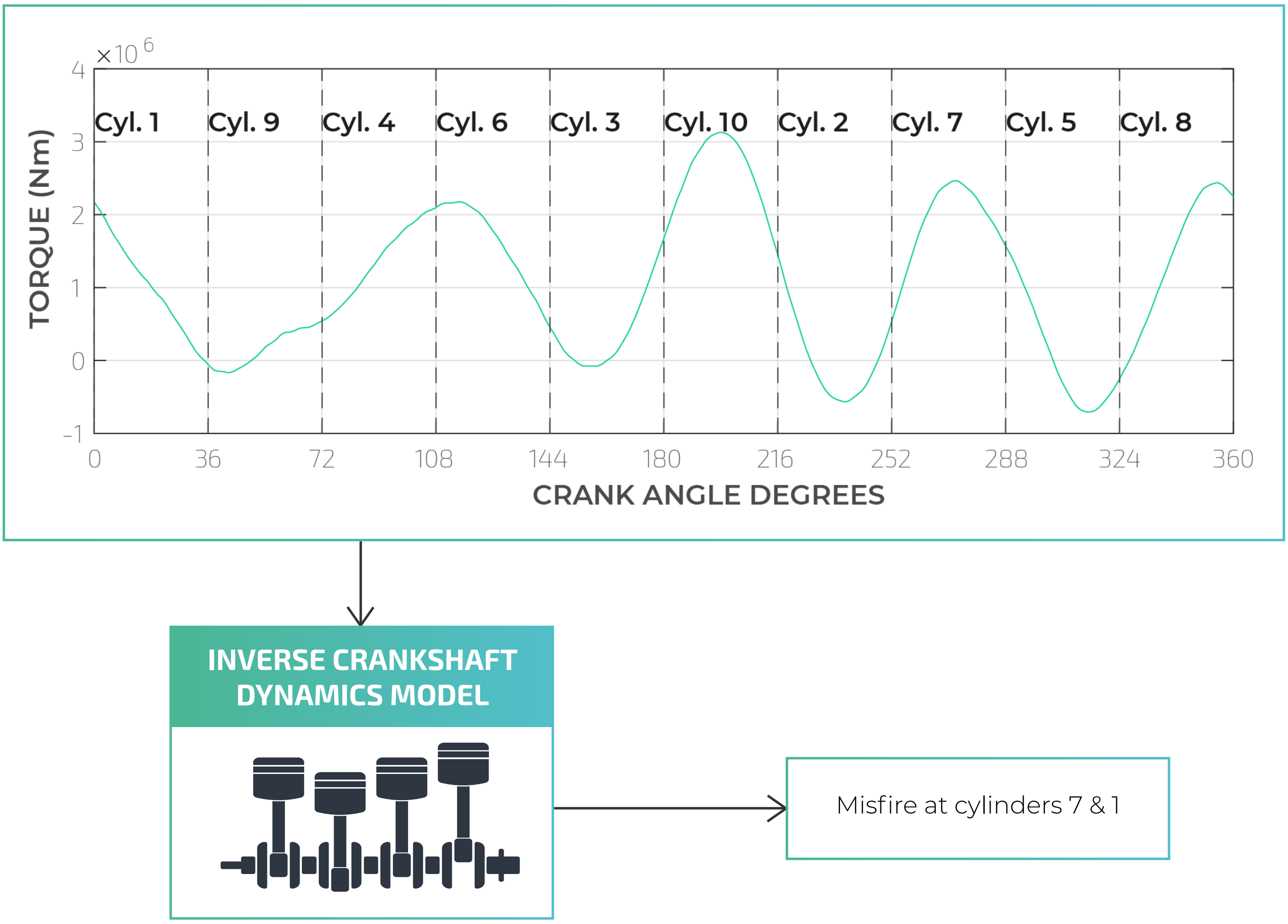


Instantaneous crankshaft torque of a 2-stroke, 10-cylinder engine, in healthy vs degraded/failed condition. The fouled injector pressure diagram that results in the above torque signal can be seen above. Complete misfire refers to absence of combustion at the designated cylinder.

By establishing a baseline and mapping engine faults, an intelligent self-adaptive algorithm can be deployed on the measured torque signal such that cylinder misfiring can be detected. This is effectively the use of an inverse crankshaft dynamics model, such that with the use of the measured instantaneous crankshaft torque, the state of individual cylinders can be determined. Under a controlled simulation environment, the algorithm was able to successfully identify misfiring cylinders with a loss of 30% in maximum combustion pressure.

> ***"Under a controlled simulation environment, the algorithm is able to successfully identify misfiring cylinders with a loss of 30% in maximum combustion pressure."***

An example for cylinders 7 and 1 misfiring is shown below:



Identification of misfiring in a 2-stroke 10-cylinder engine via the inverse crankshaft dynamics model for the case of cylinders 7 and 1.

05

WHAT THE FUTURE HOLDS

Understanding the crankshaft's dynamics allows for the use of the instantaneous crankshaft torque as a highly reliable measurement that allows for an in-depth look into the engine's condition.

The above acts as the start to the continuous development of intelligent engine diagnostics, which in the future will incorporate a multitude of additional measurements of critical engine components, such as the turbocharger, air & oil coolers, etc. in order to holistically perform condition based maintenance on the entire engine system.

Hence, such measurements will be used to identify component-wise degradation trends and failures by means of coupling a data driven thermodynamics model with the crankshaft dynamics model, which will enhance the detail and accuracy of the engine diagnostics. In addition, with more training data available, the robustness of the intelligent self-adaptive algorithm will improve, such that it will be able to predict more precisely the in-cylinder pressure as a result of changes in the instantaneous crankshaft torque signal.

Lastly, frequency analysis on the torque signal will be incorporated, as it provides information of the mechanical health of the engine, through which failures such as piston scuffing and excessive bearings wear and tear can be identified.

Thus, by incorporating the above, a decision support tool will be developed, offering a targeted bottom-up approach to fuel and maintenance savings.