YRKESHÖGSKOLAN NOVIA

Simulating Torsional Vibrations at Engine Assembly Line

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BACHELOR'S THESIS

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Abstract

This thesis was commissioned by Wärtsilä Marine Power for the Automation and Control department. In Wärtsilä a new engine safety system module has been developed. The functionality of this engine safety system will be tested at the engine assembly line in accordance with defined quality checks done when the engines are manufactured. In the engine safety system, there is a functionality to detect the torsional vibrations in the crankshaft of the engines.

The purpose of this work was to explore if it is possible to simulate the torsional vibrations of the crankshaft in an internal combustion engine with a test rig consisting of an electric motor and a gearwheel. This would be accomplished by first studying the functionality of the torsional vibration detection and then searching for, identifying, and testing the ability of appropriate electric motors to simulate this.

This thesis explores the phenomena of torsional vibration, describes the functionality of the torsional vibration measurement in the engine safety system as well as explains the working principle of some electric motors. Further, the suitability of the electric motors for the simulation is discussed.

The result of this thesis work is a better understanding of the system and what is needed to simulate torsional vibrations with the test rig. Further tests would need to be done to be able to fully decide on the way to go but this material provides a good overview of the challenges with the simulations and suggest possible solutions to the problems.

Language: English
Key words: torsional vibration, simulating, engine, safety, electric motors

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Abstrakt

Detta examensarbete beställdes av Wärtsilä Marine Power för avdelningen Automation and Control. Man har vid Wärtsilä utvecklat en ny säkerhetsmodul för motorernas säkerhetssystem. Funktionaliteten av denna säkerhetsmodul och säkerhetssystem kommer att testas vid monteringslinjen för motorerna i enlighet med definierade kvalitetskontroller som görs när motorerna tillverkas. En av funktionaliteterna i säkerhetssystemet är mätning av vevaxelns vridningsvibrationer.

Syftet med detta examensarbete var att undersöka ifall det är möjligt att simulera vridningsvibrationerna som uppstår i en förbränningsmotors vevaxel med hjälp av en testrigg bestående av en elmotor och ett kugghjul. Detta skulle åstadkommas genom att först studera funktionaliteten av vridningsvibrationsmätningarna och efter detta söka efter, identifiera och testa lämpliga elmotorer att simulera detta med.

Detta examensarbete undersöker fenomenet med vridningsvibrationer och förklarar funktionaliteten hos vridningsvibrationsmätningarna i säkerhetssystemet för Wärtsiläs motorer. Vidare förklaras arbetsprincipen för några elmotorer och dessa motorers förmåga att simulera vridningsvibrationer diskuteras.

Resultatet av examensarbetet är en bättre förståelse över systemet och vad som krävs för att simulera vridningsvibrationer med testriggen. Ytterligare tester behöver göras för att kunna identifiera den bästa lösningen, men detta material ger en bra överblick över utmaningarna med simuleringen och föreslår möjliga lösningar på problemen.

Språk: engelska
Nyckelord: torsional vibration, simulering, motor, säkerhet, elektrisk motor

Table of contents

List of Abbreviations

AC	Alternating Current
BLDC	Brushless Direct Current
DC	Direct Current
ESM	Engine Safety Module
HSR	High-availability Seamless Redundancy
ICE	Internal Combustion Engine
PWM	Pulse Width Modulation
RPM	Revolutions Per Minute
SIL	Safety Integrity Level
TDC	Top Dead Center
TV	Torsional Vibration
TVA	Torsional Vibration Analysis
UNIC	UNIfied Controls (On engine automation system) [1]

1 Introduction

Monitoring of torsional vibration in rotating parts has proven to be a good way to observe the health of various power transmitting systems and their components. The source of the torsional vibration differs across systems, but some common sources are for example unbalanced components, uneven rotational force and couplings.

In an internal combustion engine, the moving assembly (connecting rod and piston) applies an uneven force on the crankshaft which makes the speed of the crankshaft fluctuate. By monitoring this fluctuation (torsional vibration) it is possible to determine if the engine is working as it should or if there are some problems in the operation.

In this initial chapter, I will give a brief introduction about Wärtsilä and then present some background information to the thesis work as well as further clarify the purpose of the work. Lastly, there will be a disposition that describes the layout of the following chapters and their contents.

Some information that is discussed in the thesis is classified as sensitive material and will therefore not be published to the general public. In the public version of the thesis the chapters containing this information will be marked as “Confidential” and the contents will be removed.

1.1 Wärtsilä

Wärtsilä was established in eastern Finland as a sawmill in the year 1834. Since the beginning the business area has changed and evolved several times and today Wärtsilä is a global company and actor in the marine and energy markets. Wärtsilä provides lifecycle solutions and innovative technologies to these markets and their portfolio consists of many different products besides their engines that they are most widely known for. The main focus for the company at the moment is on the decarbonisation transformation and fossil-free fuels for the future. [2] [3]

The headquarter of Wärtsilä is in Helsinki and the company had about 17500 employees at the end of 2022, the employees are located in more than 240 locations in 79 countries. In the year 2022 the net sales came to a total of 5,8 billion euros which resulted in an increase of 22% compared to the previous year. The operations are divided into three main business units which are Wärtsilä Energy, Wärtsilä Marine Power and Wärtsilä Marine Systems. [2]

1.2 Background

This thesis is written for the Wärtsilä Marine Power, R&D, Automation and Control department. I have worked in a division of this department as a trainee for two years and when it was time to start my thesis work, I got an opportunity to write it for Wärtsilä. The subject was proposed by my line manager who also is one of the supervisors for the thesis.

At Wärtsilä a new engine safety system has been developed to monitor the engine's operation and protect their components. One of the functionalities of this safety system is to monitor the engine health by looking at the torsional vibrations of the crankshaft. By monitoring the torsional vibrations, it is possible to detect severe abnormalities in the engine and take actions to prevent major breakdowns. The torsional vibration is calculated and derived from data that the speed sensors provide to the system. This functionality has been tested and proven to work but it would be good to have a way to test and verify the functionality at the engine assembly line using the safety system and speed sensors used in the specific engine that is assembled.

1.3 Purpose

The purpose of this thesis is to explore the possibility to simulate and test that the torsional vibration measurement is working using the engine specific speed sensors and safety system. For simulating a running 4-stroke engine a test setup consisting of an electrical motor driving a gearwheel will be used. This test setup will be used to test that the speed sensors and speed input into the engine control system work after it has been assembled on the engine. This thesis will research and explore if it is possible for the test setup to mimic the torsional vibrations from an engine and in that way also verify that this functionality is working in the assembly tests.

1.4 Disposition

The first chapter in this thesis provides an introduction to the subject of torsional vibration. It also gives information about the company, some background to the work and the purpose of the thesis work itself.

The second chapter will explain the phenomena of torsional vibration and give some information about the sources and control of it.

The third chapter introduces the engine control system and gives some information about the new engine safety module and the working principle of the torsional vibration protection functionality that is implemented into the module.

The fourth chapter will investigate different electrical motors and their working principle to get a better understanding of what kind of motor that suites this simulation the best.

In chapter five the electrical motors’ suitability for the simulation will be discussed and some challenges of the simulation will be presented.

Chapter six will present the result of the thesis and in chapter seven the work will be discussed, and a conclusion of the work done will be made. Further research and tests that would need to be done in order to validate the suitability of the electric motors will also be presented in chapter seven.

2 Torsional Vibration

Torsional vibration (TV) is according to Wärtsilä defined as “The twisting of a shaft or any other structure about an axis in a cyclical manner due to a varying applied torque.” [4] The TV can furthermore be defined as angular vibration or twisting vibration in a rotating object, usually a shaft, along its axis of rotation. [5]

2.1 What is Torsional Vibration

When different forces impact a rotating shaft at separate locations along the length of the shaft, the shaft will flex to some degree. This occurs as no material can be infinitely stiff and there will always be some flex in the components. The flex introduces speed fluctuations into the shaft and there will be a change in the rotation speed of the shaft as the flex travels through the shaft. It is these speed fluctuations that are normally known as and called torsional vibration. [5] [6]

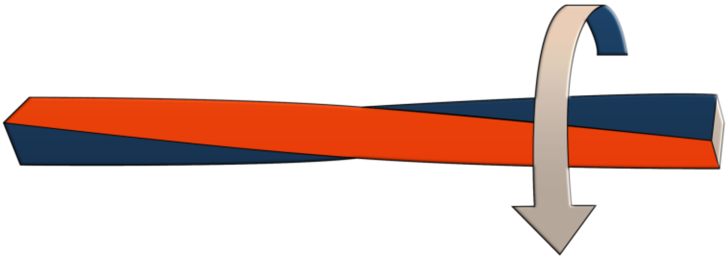

Figure 1. Illustration of a twisting shaft *[8]*

For a simple example, one can imagine a rubber rod attached to a weight shaped like a circle in one end. If the rubber rod is rotated at a steady rotation speed the weight in the end will also rotate in the same speed as the rod. If the rotation of the free end of the rubber rod is accelerated, we change the force that is impacting this end of the “shaft”. As the weight in the other end has a certain amount of rotational inertia before it accelerates to the same speed as the free end of the rubber rod, the rubber rod will twist around its own axis before the weight is up to the same speed. This will then make the weight oscillate back and forth in rotation speed as the rubber rod will twist in both directions until the weight has stabilised its rotation speed to the new rotation speed of the rubber rod. If the rotation speed of the rubber rod is continuously changed every revolution the twisting of the shaft and the oscillation of the weight will not stop, and torsional vibration of a certain frequency will occur in the rubber rod.

In the example above the shaft is very flexible and it is easy for the weight to oscillate back and forth once it got momentum to it. In a real scenario the shaft would not flex to this extent, but it will still flex and behave in a similar manner although the flexing can't be observed without measuring equipment. Some examples of measuring equipment that can be used to measure TV are a magnetic pickup measuring a gear or an optical sensor measuring a shaft wrapped in zebra tape. With this kind of measuring equipment, it is possible to measure and compare the speed of rotation several times in one revolution and therefore identify if the speed is fluctuating.

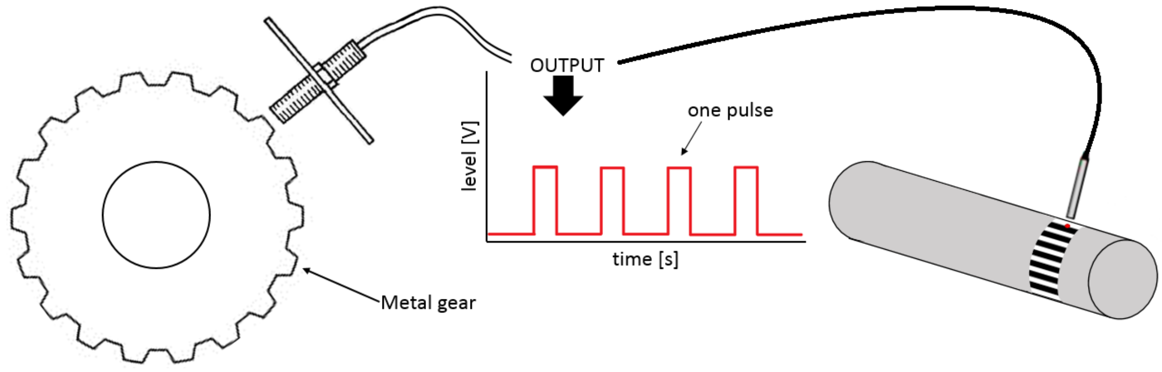

Figure 2. Magnetic sensor to the right and optical sensor to the left used for detecting torsional vibration in shafts *[7]*

The twisting of shafts needs to be accounted for and controlled when a part is designed. Excessive torsional vibration in a component or a power-delivering system causes problems that in some cases can be devastating, some examples are noise problems in gears, excessive wear on components, or even critical failures of components such as axel cracking or snapping.

In an internal combustion engine (ICE), the crankshaft is the main component that is exposed to torsional vibration. This is due to the long length of the crankshaft and the way the power is produced and delivered through the shaft. When the engines get bigger there is more flex in the crankshaft as it is longer, which results in more TV. There are also other components in an ICE that experience TV, for instance the camshaft, but the focus will be on the crankshaft in this work. [5] [7] [8]

2.2 Sources of Torsional Vibration

There are many different sources of torsional vibration depending on the specific system and its characteristics. For example, in electrical motors there are distinct poles that cause vibrations in speed, misalignment of shafts will cause vibrations in the system and a non-smooth power outtake such as an elastic belt drive can introduce vibrations into a system.

In an internal combustion engine, there are also many sources of torsional vibration as the engine has many parts that move and affect each other with forces in multiple directions. As the sliding assembly, piston and rod, move up and down in the cylinder there will be forces transferred to the crankshaft in both directions mainly from the compression event and the combustion event. These forces will make the speed of the crankshaft fluctuate, for example when there is combustion in one cylinder the piston will transfer the combustion force to the crankshaft and accelerate it, and correspondingly when the position compresses the air and fuel in the cylinder there will be a force that decelerates the crankshaft. As this is a fundamental event to the working principle of the ICE there will always be some degree of torsional vibration in an ICE, but it can be controlled and reduced through different methods that will be discussed in the next subchapter.

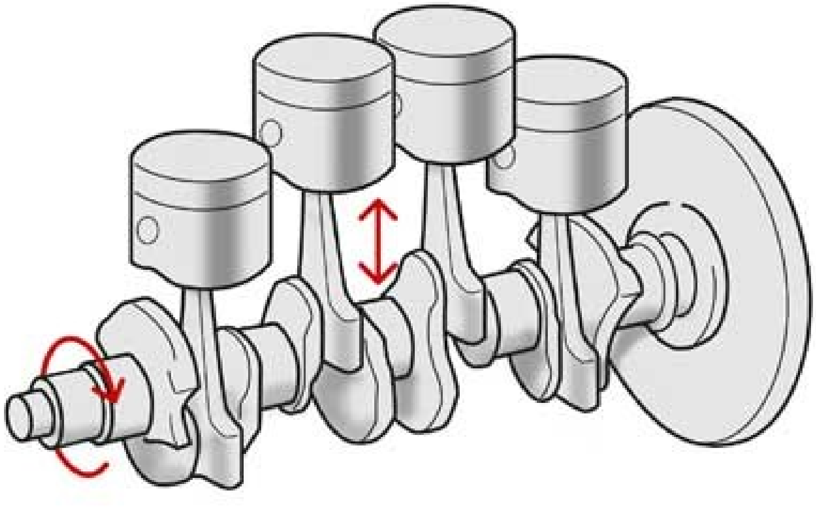

Figure 3. A rotating assembly of an internal combustion engine, the pistons and rods affect the crankshaft with forces in both directions *[9]*

This "natural" occurring TV can be controlled and accounted for but there is also a possibility of malfunctions in the operation that can introduce peaks or a higher level of TV into the system. If for example, a piston is seizing in the cylinder there will be a large force transferred to the crankshaft in order to free the piston. Other examples of malfunctions that introduce excessive torsional vibration are engine knock, engine misfire, worn joints etc. If the torsional vibrations are measured and analysed there is a possibility to detect these faults and take actions before they do any severe damage to the system. [6] [7]

2.3 Control of Torsional Vibration

There are several different methods that can be used to control the level of torsional vibration in a component or system. The first is obviously to design the components well and remove any imbalances and try to reduce the sources of torsional vibration, through for example crankshaft counterweights, but this is not enough many times and there can still be a high level of TV in the component due to the dynamics of the system.

One method that is widely used to reduce TV is vibration dampers. These are normally mounted on the end of a shaft and are tuned to damp vibrations of a certain frequency to avoid resonances in the shaft. There are different kinds of vibration dampers that work a little differently from each other but the principle of having weight attached through a damping material that in turn dampens the vibrations is the same in most of them.

Another method is to mount a flywheel to the shaft and have the weight of the flywheel to smoothen out the rotation speed. As the flywheel rotates it will store the mechanical energy of the system and the speed of the rotation can’t fluctuate as easily due to the rotational inertia which in turn will reduce the amount of torsional vibration in the shaft. The flywheel will reduce the fluctuations of the rotation in general but in some cases this will make the shaft flex even more as this adds a rotation torque to the system.

Elastic couplings are yet another method to reduce TV in rotation and power-delivering systems. The working principle of them is that the load is attached to the power source through an elastic component, for example rubber or springs, and this medium then takes up some of the vibration and converts it to thermal energy.

In big marine internal combustion engines, all the methods mentioned above are normally implemented to help with reducing the torsional vibration in the crankshaft. There is usually a vibration damper mounted in the free end of the engine, with the free end meaning the end of the crankshaft that is not driving the load. The vibration damper can be integrated into a pulley that is driving some auxiliary loads on the engine, but it can also be a unit of its own. In the driving end of the engine the flywheel is located and to the flywheel there is usually an elastic coupling mounted which in turn is connected to the load that can be for example a generator or a propeller shaft. [5] [10]

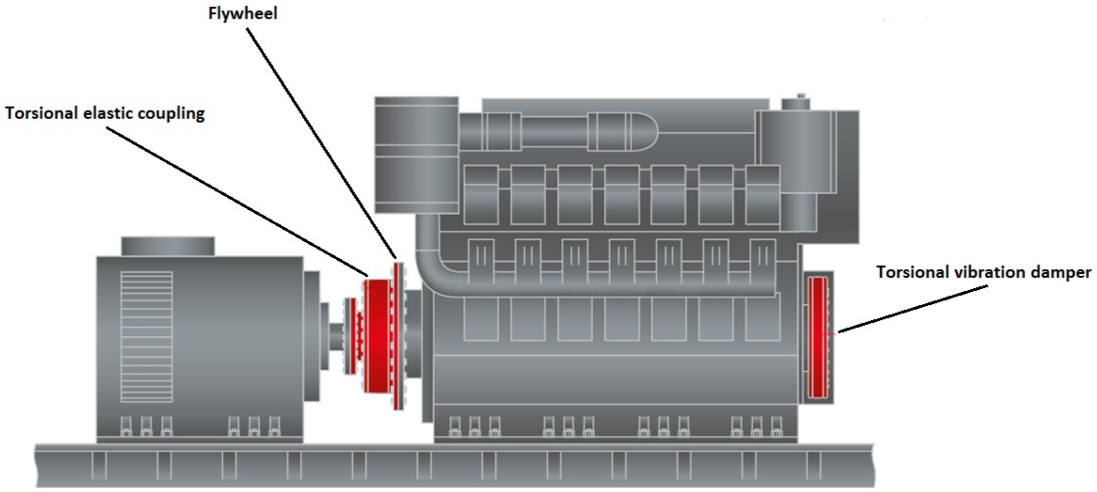

Figure 4. Visualization of torsional vibration control methods on a marine engine genset *[10]*

3 Wärtsilä UNIC

UNIfied Controls (UNIC) is an engine control system developed by Wärtsilä for their 4-stroke engines, it controls the operation of the engine and makes the operation safe, flexible, and reliable. The system is a so-called embedded system and is designed to meet high standard levels of reliability and quality. The design is modular and can easily be scaled up or down to fit different engine sizes and layouts. The system consists of UNIC modules of different kinds that are mounted directly on the engine to achieve a compact system with short wires and fewer points of failure. In Figure 5 an overview of how the UNIC system could be put together is presented, the normal layout and placement of the modules can be seen in the figure. [1]

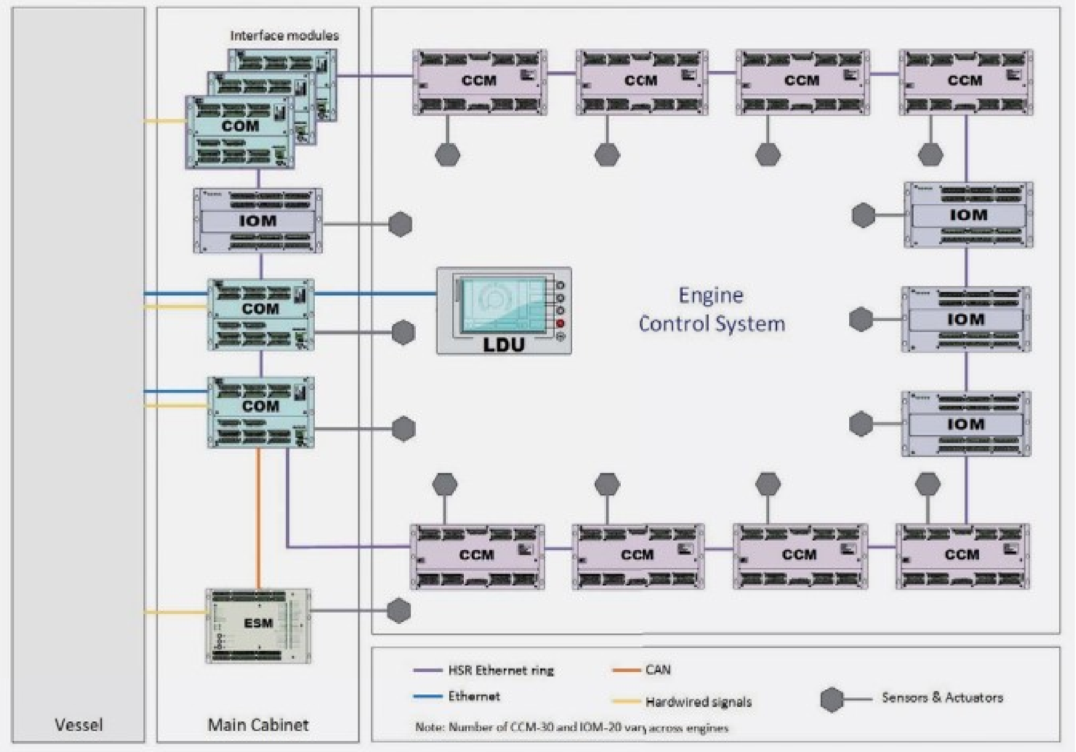

Figure 5. Wärtsilä UNIC system overview *[1]*

3.1 Module Types

As mentioned above the UNIC system consist of different modules that control and handle different tasks in relation to the engine operations. The modules are connected and communicate with each other through a High-availability Seamless Redundancy ethernet ring (HSR-ring). The following list will give a short introduction to the modules there are. [1]

LOP - Local Operator Panel consists of a local display unit (LDU) and control buttons, the LDU displays information about the engine and its operations. It is possible for the operator to control the engine from the LOP with pushbuttons and an emergency stop button. The main task of the LOP is to give an overview of the operations and provide a function to control/reset the system.

COM – Communication Module is the main module in the system and is the gateway between the UNIC system and other systems. The communication module controls many functions in the system and manages the software and configuration updates of the system. There are at least two COM modules in the system for redundancy reasons, but the number can be higher depending on the extent of the control system.

CCM – Cylinder Control Module controls the cylinder-wise operations and manages functions related to combustion, for example injection, valve timing etc. The amount of CCM modules in the system depends on the number of cylinders in the engine.

IOM – Input/Output Module handles measurements from sensors and control devices in the area of the engine where they are mounted. They are normally placed at the ends of the engine and close to the devices and sensors they are connected to which simplifies wiring. The number of modules depends on the type and size of the engine as well as the application the engine is used in.

ESM – Engine Safety Module is handling safety functions that are related to the safety of the crew that operates the engine and the surroundings in case there would be a fault with the engine. The engine’s components are also protected by the ESM to some degree as the engine is brought into a safe state in case of abnormalities. Shutdown due to low oil pressure or overspeed are examples of safety functions that ESM is controlling.

[1]

3.2 Engine Safety System (Confidential)

3.2.1 Speed Measurement (Confidential)

3.2.2 Torsional Vibration Calculation (Confidential)

4 Electrical Motors

There are electrical motors of various models and types, and all have different use cases with their advantages and disadvantages. In this chapter the working principle of a few motor types will be described briefly, these motors have been identified as suitable for this kind of simulation. Figure 6 gives a good overview of the mechanical structure of the motors discussed in this chapter.

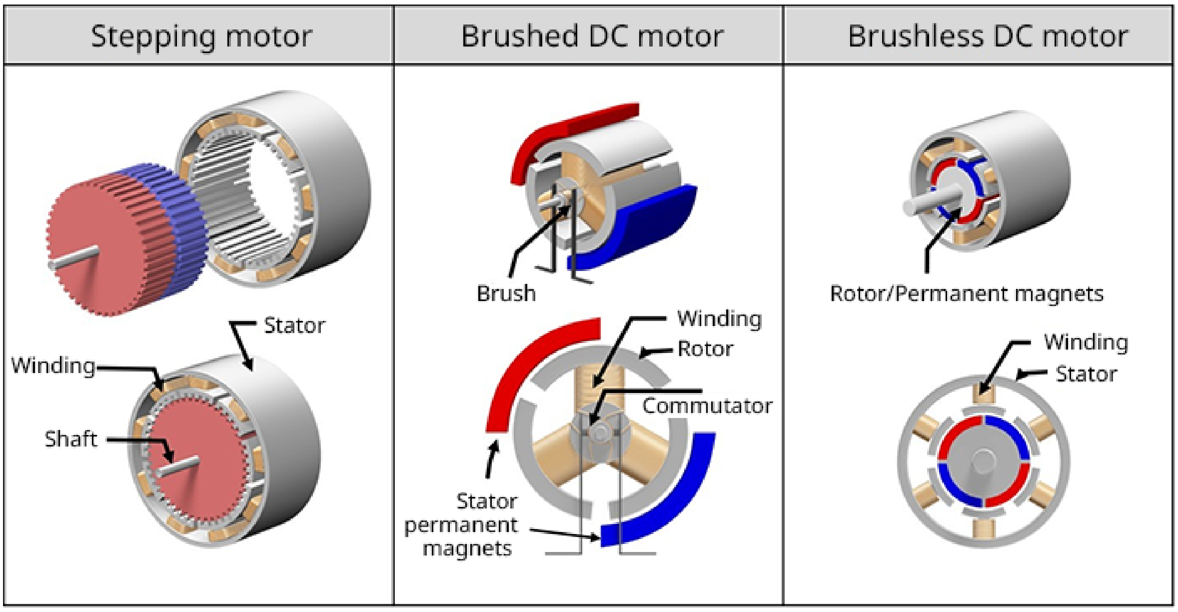

Figure 6. Comparison of the motor construction between stepper motors, brushed DC motors and brushless DC motors *[11]*

4.1 DC Motors

A DC motor can be built up in different ways and the characteristics of the motor changes with how it is constructed. For example, there are brushed DC motors and brushless, and there are different ways of making the windings and different driver logics. In this subchapter the brushed DC motor along with the brushless DC motor will be explored, the working principles of these will be briefly presented. [12]

4.1.1 Brushed DC Motor

A brushed DC motor is one of the simplest kinds of motors to make and control and is found in all different sizes. DC motors were the first form of electrical motors widely used and up until the 1980s the brushed DC motor was the main motor used when speed and torque control were needed.

The brushed DC motor has rotor windings that are exited through the commutator, the power is connected to brushes that have a sliding connection to the windings in the rotor. As the rotor spins the commutator is designed so that the windings in the rotor will change polarity and the forces in them will alternate. This creates a rotating magnetic field inside the rotor, it is this rotating magnetic field that makes the rotor spin constantly as long as power is supplied to the motor. The stator in the brushed DC motor can be constructed of field windings (electromagnets) or it can be built up of permanent magnets, in the case of electromagnets these also need power connected to them to create a magnetic field.

Figure 7 illustrates the concept of the brushed DC motor. The stator is constructed of permanent magnets and the rotor consists of one winding. As the current travels through the winding there will be a magnetic field created around the winding. This magnetic field will react with the magnetic field of the stator and the rotor will be forced to spin. When the rotor has rotated half a turn the polarity in the winding will change and it will again be forced to rotate half a turn. As the number of poles in the stator and the number of windings in the rotor is increased the rotation created will be smoother and the torque delivered will be more linear. [12] [13] [14]

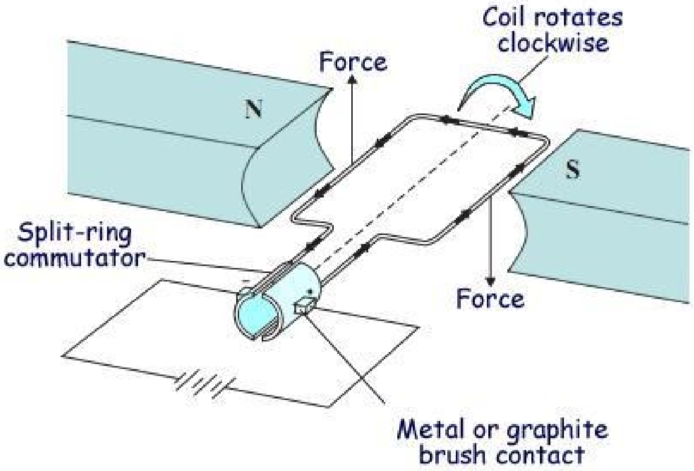

Figure 7. A very simplified illustration of a brushed DC motor with a two-pole permanent magnet stator and one rotor winding *[13]*

4.1.2 Brushless DC Motor

In a brushless DC (BLDC) motor, the rotor is the part that has a steady magnetic field provided by permanent magnets and it is the magnetic field of the stator that rotates in order to rotate the rotor. In other words, you can say that the brushless DC motor is a brushed DC motor with permanent magnets turned inside out, the magnets of the stator have changed place with the windings of the rotor. Further, you can say that a brushless DC motor is more similar to an AC motor in its construction, in fact the BLDC motor is essentially a kind of AC motor driven by DC power that is switched to the windings in a pulsating manner therefore creating an alternating current.

As mentioned, the rotor is the part that has permanent magnets in the BLDC motor, and due to this there is no need for brushes or any kind of electrical connection to the rotor, this simplifies the construction and lowers the maintenance of the motor as well as increases the efficiency of the motor. Instead, the current in the stator windings is switched to create the rotating magnetic field and the movement in the rotor. To control the stator windings there is a need for an electronic controller/driver that controls which windings that should be exited and in which direction the current shall go.

The driver of a BLDC motor needs to know the position of the rotor to be able to know which stator winding to activate. This is normally done by hall effect sensors that are integrated into the motor housing and measure the position of the rotor shaft. The outputs from these sensors are then connected to the motor driver and the logic inside the driver determines which winding to energize. [12] [14]

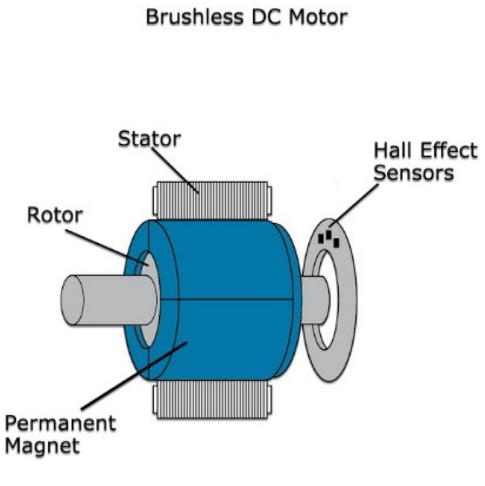

Figure 8. Illustration of a brushless DC motor that has the permanent magnets on the rotor and the stator windings around, the hall effect sensors used to determine the rotor position can also be seen. *[14]*

4.2 Stepper Motor

A stepper motor is built similarly to a brushless DC motor, but the working principle is a little bit different. Instead of having the magnetic field in the stator to force the rotor to rotate it pulls the rotor to a specific position. The stepper motor divides one revolution into several steps and is then driven by pulses that rotate the motor one step at a time. It manages this task by having an iron core that is machined to have groves that line up with similar groves in the stator poles. When the windings in one stator pole get energized the magnetic field introduced into the pole pulls the groves on the rotor to line up with its own groves. As the next stator poles groves are a little offset from the previous one, the rotor will again rotate a bit to line up with it as it is energized.

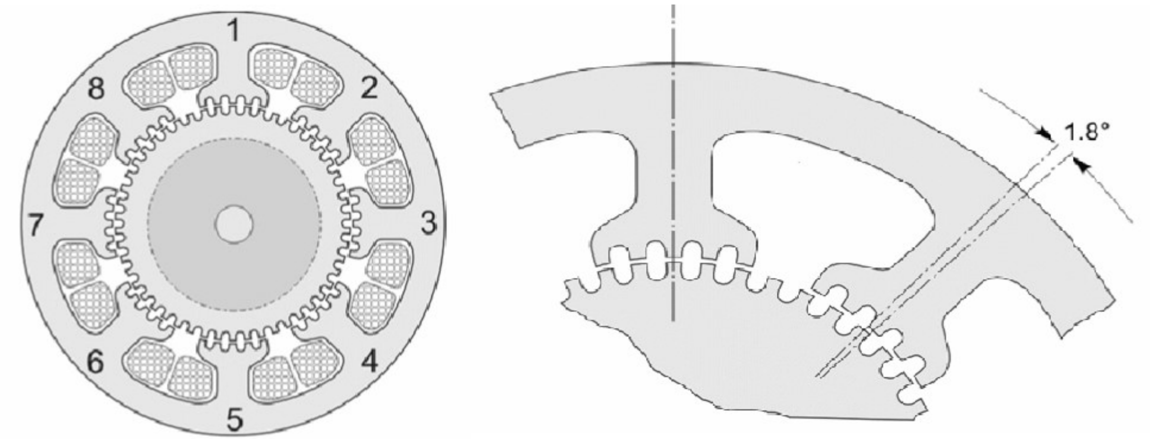

Figure 9. Visualization of the structure in a stepper motor having a step angle of 1,8deg, resulting in 200 steps each revolution *[12]*

For each pulse sent to the stepper motors driver the motor is rotated one step. This gives precise control of the position and speed of the motor's rotation. The number of steps in one revolution varies depending on the design of the rotor and stator but can be anywhere between 4-200 and even higher in some cases. Each step is completed very fast and if a series of pulses is sent to the stepper motor in a short amount of time the revolution becomes smooth. It then behaves like a normal electric motor but with the remaining control of each step that it rotates.

Stepper motors have high torque at low speeds but when the speed gets higher the torque is reduced drastically and the strength of the motor is significantly lower. There is no lower limit of the speed range of a stepper motor, it can operate from 0 rpm and upwards. The maximum speed on the other hand is normally around 1000 rpm depending on the motor type and size but can be higher in some models. [12] [15] [16]

5 Simulating the Torsional Vibrations (Confidential)

5.1 Electric Motor Selection (Confidential)

5.2 Pulse Train (Confidential)

5.3 Test of the Electric Motor (Confidential)

6 Result

The result of this thesis is a theoretical investigation of the electric motors suitable for the simulations. As it was not possible to perform the tests on the test rig the work was limited to a comparison between the suitable motors and their working principles. The advantages and disadvantages of the motor types are compared and held against the requirements of the simulation. Further, some more aspects of the simulation are identified and discussed throughout the document.

There are a few concerns with the brushless DC motor and its ability to react fast enough for these simulations. Due to this the stepper motor might be a more suitable motor for the simulations and the control of this one is also discussed in the document. The stepper motor provides an enhanced control over the rotation and the position of the rotor which could be beneficial in this kind of simulation to obtain the desired torsional vibrations.

A small-scale test was performed and the speed fluctuations with a small DC motor were tested. This test mainly provides experience and, in some way, validates the principle of the simulations. As the frequency of the fluctuations in this test is much smaller than for the fluctuations needed to simulate the torsional vibrations, it is not possible to determine if it is working in the actual test rig based on this. It will therefore have to be tested and verified how the test rig responds as the frequency of the fluctuations is increased and as peaks in the rotation speed are introduced.

7 Discussion

The work with the thesis has been interesting and I have accumulated a lot of new knowledge. As I have worked as a trainee for some time already at Wärtsilä I had some knowledge about the engine control system, but this work has deepened my understanding of the system and certain control functions in it. I have also developed my knowledge about small electrical motors with their control systems and different characteristics.

The most challenging part was to do the research work and to obtain an understanding of how the safety system works with the torsional vibration calculation and everything. As I was not so familiar with torsional vibrations from before quite much time has been laid on research and learning about the torsional vibrations and how they behave.

As mentioned in the result tests of the simulations could unfortunately not be performed, these tests would have added more value to the thesis work and made the result of the thesis even closer to a ready concept for a simulation. Although the tests were not possible to perform the content of this thesis gives a good overview of the simulation and what is needed going forward with the concept.

7.1 Further Work

The next step towards simulating the torsional vibrations would be to test the test rig with the current DC motor and validate its suitability. If it turns out that the DC motor currently used on the rig is not able to simulate this a stepper motor would be the next step and tests of this should then be performed.

When the suitable motor has been identified further work will be needed to implement the control of the motor into the test rigs control system. More knowledge about the torsional vibration of the engines simulated will be needed in order to construct the specific pulse train for the simulations. The control of the level and characteristics of the torsional vibrations can advantageously be implemented into the control system of the test rig so that it could be changed in different ways during the operation to activate the safety functions in the engine’s safety system.

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