DESIGN OF A DYNAMOMETER-ENGINE COUPLING SHAFT

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Abstract

In measuring the power output of an engine, the engine has to be coupled to a load device known as dynamometer. The coupling is done by means of a solid shaft. The proper couplings and shaft are required for the connection to avoid any failure to the engine or the dynamometer. Unsuitable selection could lead to undesired problems such as torsional vibrations, vibration of the engine and dynamometer, whirling of the coupling shaft, damage of the bearings, engine starting problem or immoderate wear of the shaft line components. The commonly encountered problem is the resonance in torsional vibration, which results in disastrous failure of the shaft due to excessive vibration. This project is aimed to study the appropriate design of the shaft to be used in the dynamometer-engine coupling to prevent the system from undergoing unwanted problems. The theoretical calculations involve in the design are presented. The dimension of the coupling shafts for engines with various maximum torques are estimated. It is shown that the diameter of the shaft is proportional to the maximum torque of the engine given that the same coupling is used for every system, whereas the length of the shaft is almost equal for every engine. The diameter of the shaft is a vital parameter compared to its length. For engines with the maximum torque vary from 40 to 200 Nm, the same shaft length of 500 mm can be used but with increasing shaft diameter as the maximum torque increases. For a 40 Nm engine, the shaft diameter of 20 mm generated acceptable result. The shaft diameter was increased by 5 mm as the maximum torque increases and acceptable results were obtained. On the other hand, by using aluminium instead of steel as the material of the shaft, lower critical engine speed is obtained given that the same dimension of the shaft is used. This is due to the fact that aluminium possesses lower modulus of rigidity in comparison to steel.

Abstrak

Di dalam mengukur kuasa yang dijana oleh sesebuah enjin, enjin perlu disambungkan kepada sebuah mesin dikenali sebagai dinamometer. Penyambungan dilakukan dengan menggunakan syaf yang padat. Syaf dan perangkai yang sesuai diperlukan untuk mengelakkan sebarang kerosakan pada enjin atau dinamometer. Pemilihan yang tidak bersesuaian boleh mengakibatkan berlakunya masalah-masalah yang tidak diingini seperti getaran kilasan, getaran pada enjin dan dinamometer, pemusingan pada syaf perangkai, kerosakan pada galas, masalah untuk menhidupkan enjin dan kerosakan teruk pada komponen-komponen syaf. Masalah yang paling biasa dihadapi ialah resonan pada getaran kilasan yang boleh mengakibatkan kerosakan teruk pada syaf disebabkan oleh lebihan getaran. Projek ini disasarkan untuk mengkaji tentang rekabentuk syaf yang sesuai untuk diaplikasikan di dalam sistem dinamometer-enjin bagi mengelakkan sistem daripada dilanda masalah yang tidak diingini. Pengiraan secara teori yang terlibat didalam proses merekabentuk dipersembahkan didalam kajian ini. Dimensi syaf perangkai bagi enjin-enjin yang berlainan nilai tork maksimum adalah dianggarkan. Kajian ini menunjukkan bahawa diameter syaf berkadar terus dengan nilai tork maksimum enjin, dengan semua system menggunakan perangkai yang sama, tetapi panjang syaf adalah hampir sama bagi semua enjin. Ini menunjukkan diameter syaf adalah lebih penting daripada panjangnya. Bagi enjin-enjin dengan nilai tork maksimum berbeza daripada 40 hingga 200 Nm, panjang syaf yang sama iaitu 500 mm boleh digunakan tetapi dengan diameter syaf bertambah bagi setiap peningkatan nilai tork maksimum. Bagi engine dengan 40 Nm tork, diameter syaf sebesar 20 mm menghasilkan keputusan yang boleh diterima. Diameter syaf dibesarkan sebanyak 5 mm dengan nilai tork maksimum enjin meningkat dan keputusan yang memuaskan diperoleh. Dalam pada itu, dengan menggunakan syaf yang diperbuat daripada aluminium berbanding besi, kelajuan kritikal enjin yang lebih rendah diperolehi dengan

menggunakan syaf yang berdimensi sama. Ini kerana aluminium mempunyai modulus ketegaran yang lebih rendah berbanding besi.

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List of Symbols and Abbreviations

n	Frequency of torsional vibration	[cycles/min]
n_c	Critical frequency of torsional vibration	[cycles/min]
C_s	Stiffness of coupling shaft	[Nm/rad]
I_e	Rotational inertia of the engine	[kg m^2]
I_b	Rotational inertia of the dynamometer	[kg m^2]
T	Torque	[Nm]
T_{ex}	Amplitude of exciting torque	[Nm]
θ	Amplitude of torsional vibration	[rad]
θ_0	Static deflection of shaft	[rad]
M	Dynamic magnifier	
M_c	Dynamic magnifier of critical frequency	
N_0	Order of harmonic component	
N_{cyl}	Number of cylinders	
M_{mean}	Mean turning moment	[Nm]
$imep$	Indicated mean effective pressure	[bar]
B	Cylinder bore	[mm]
S	Stroke	[mm]
T_m	Component of tangential effort	[Nm]
T_v	Amplitude of vibratory torque	[Nm]
N_c	Engine speed corresponding to n_c	[rev/min]
τ	Maximum shear stress in shaft	[N/m^2]
N_w	Whirling speed of shaft	[rev/min]
N_t	Transverse critical frequency	[cycles/min]
C_c	Dynamic torsional stiffness of coupling	[Nm/rad]
ψ	Damping energy ratio	
E	Modulus of elasticity	[Pa]
G	Modulus of rigidity	[Pa]

CHAPTER 1 : Introduction

1.1 Overview

In the automotive industry, there are a wide variety of tests conducted on the engine to measure the performance, responsiveness for acceleration/deceleration, emissions, fuel economy, durability, noise and vibration. Parameters affecting an engine's performance include the basic engine design, compression ratio, valve timing, ignition timing, fuel, lubricant and temperature [Gitano, 2008c]. Therefore, the development of vehicle cannot be realised without engine testing. However, some of these targets or parameters often work against each other [Tominaga, 2010]. Hence there are a number of specialist systems and control systems that requires isolated execution of the test.

The most commonly used prime mover in an automotive vehicle is the internal combustion engine. It produces the power through the conversion of the chemical energy in the fuel into heat followed by the conversion of the heat into mechanical work [Klingebiel & Dietsche, 2007; Pulkrabek, 2004]. This conversion takes place by means of combustion. The conversion of thermal energy into mechanical work occurs through a transmission of the energy to a working medium, which hereupon increases its pressure and subsequently produce power [Klingebiel & Dietsche, 2007]. Hence, it can be said that the internal combustion engine is an energy transformer [Crolla, 2009].

The ability of an internal combustion engine to do work is measured by a quantity known as torque. Torque is defined as the force acting at a moment distance and it is measured in newton metres (Nm). The engine creates torque and uses it to spin the crankshaft. During the power stroke, the crankshaft moves 180° from the top dead centre (TDC) to the bottom dead centre (BDC). During the movement, the effective radius of the crank-arm increases from zero (at TDC) to the maximum value in the region of mid-stroke and decreases to zero again at the end of the stroke (at BDC). The movement is illustrated in Figure 1.1 where:

- *p* is the cylinder gas pressure,
- *F* is the connecting-rod thrust,
- *R* is crank-throw,
- *r* is the effective crank radius, and
- *T* is the turning-effort or torque.

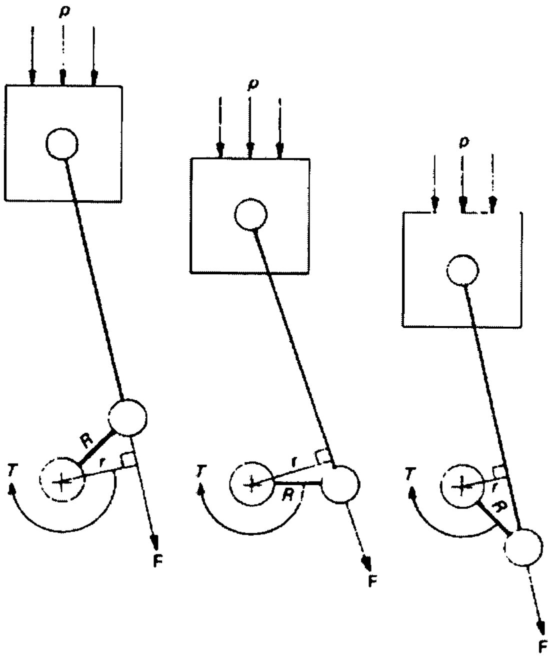


Figure 1.1 : Torque variation during power stroke. [Heisler, 1998]

This shows that the torque produced varies during the power stroke, whereas during the idling stroke, there is no useful torque generated [Heisler, 1998]. The maximum torque of an engine is known as the maximum brake torque speed (MBT). Most of the modern automobiles possess the maximum torque within the range of 200 – 300 Nm at the engine speed of 4000 – 6000 RPM [Pulkrabek, 2004].

The torque produced by an internal combustion engine is measured using a device known as dynamometer. The dynamometer resists the torque produced by the engine connected to it and measures the torque [Martyr & Plint, 2007a]. In engine testing, it is important to recreate the actual on-road situation in the most effective way in order to obtain accurate data. However, the test conducted must be safe and repeatable, thus the engine can be tested with different desired conditions [Atkins, 2009].

1.2 Background of the study

As mentioned in previous section, the internal combustion engine has to be coupled to a dynamometer in order to measure its torque. Figure 1.2 shows the illustration of dynamometer-engine setup. The engine is connected to the dynamometer by means of a shaft. The shaft has to be properly designed since a poorly designed shaft could lead to serious impairments not only to the engine, the dynamometer or the shaft, but also to the human conducting the test.

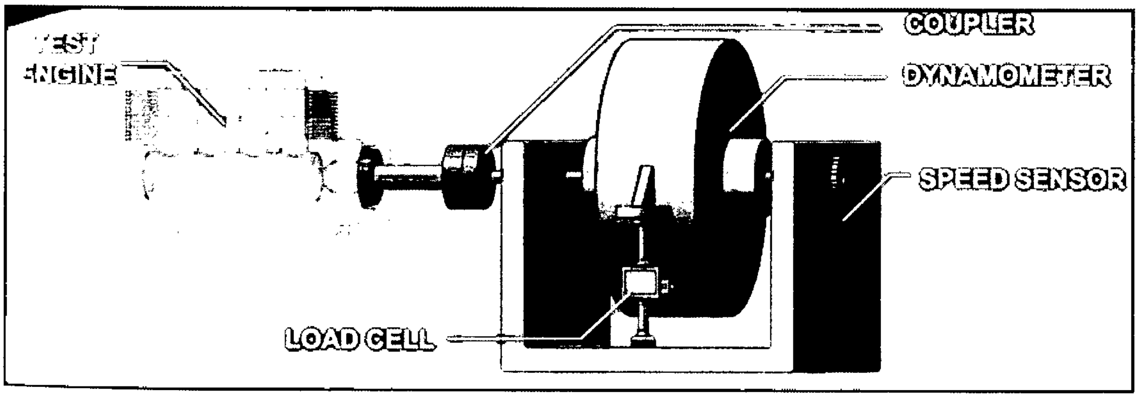
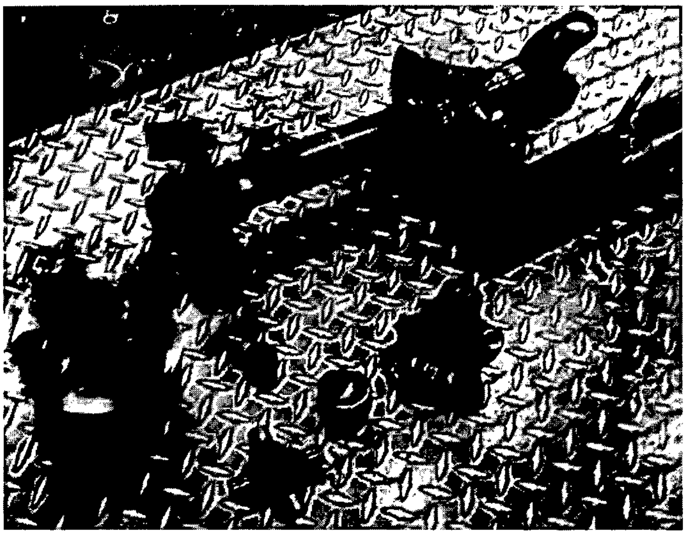
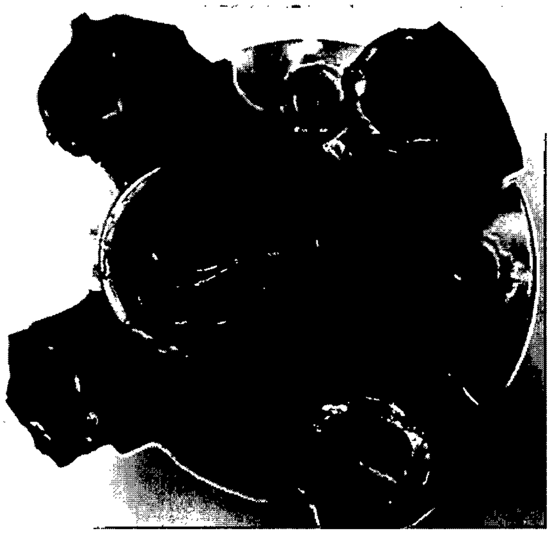


Figure 1.2 : Dynamometer-engine setup. [Gitano, 2008b]

Figure 1.3 depicts a broken shaft and a broken coupling as a result of improper designing prior to the test. The inappropriate design of the shaft could lead to various problems, namely excessive torsional vibrations, whirling of the coupling shaft, bearing damages, excessive wear of the shaft line components, engine starting problem and so forth [Martyr & Plint, 2007b]. The most commonly encountered problem in a dynamometer-engine system is the resonance of torsional vibration. The frequency of the torsional vibration depends on the inertia of the engine and dynamometer, and the stiffness of the coupling shaft. Therefore, it is vital to design a shaft with the proper stiffness to avoid the problem.



(a)



(b)

Figure 1.3 : (a) A broken shaft. (b) A broken coupling. [DynoTech-Research, 2010]

1.3 Objectives of the study

This project is aimed to study the design shaft to be used in a dynamometer-engine system. As stated in [Martyr & Plint, 2007b], the design of the shaft for different engines may differ. The objectives of this study are as follows:

1. To study the relation between the maximum torque of an engine and the design of the shaft to couple it to a dynamometer.
2. To investigate the importance of the dimensions of the shaft (i.e. shaft diameter and length) to the dynamometer-engine coupling.
3. To study the impact of using different material such as aluminium instead of steel in fabricating the shaft.

1.4 Scope and limitation

In this study, five hypothetical engines with different maximum torque values (i.e. 40, 80, 120, 160 and 200 Nm) were used. The shafts to couple these engines to a dynamometer were virtually designed to investigate the impact of maximum torque value on the shaft design. From the results, the dimensions of the shaft for each case will be observed. This study only involves theoretical calculations and the actual shafts are not fabricated. The study was conducted analytically rather than experimentally. Since hypothetical engines were used in the calculations, some parameters such as the displacement volume, bore, stroke and the moment of inertia of the engines were estimated.

CHAPTER 2 : Literature review

2.1 Introduction

There are only a few studies that were conducted regarding this topic. One of the relevant journals was published in year 2004 [Jayabalan, 2004]. In addition to it, there is a book entitled Engine Testing that contains a chapter dedicated to the dynamometer-engine coupling [Martyr & Plint, 2007b]. However, no comparison can be made since the design of the shaft differs for every dynamometer-engine setup (i.e. different engines and/or different types of dynamometer). In this chapter, the theories involve in this topic, namely the engine dynamometer and its operating mechanism, the torsional vibration/oscillation, damping and coupling, and so forth, are presented and described. They were reviewed from various journals, books, articles and brochures from manufacturers.

2.2 Engine dynamometer

To measure the torque and power output of an engine in a laboratory, the engine is coupled directly to a device known as engine dynamometer. It introduces variable loading conditions on the engine under test across the range of engine speeds and durations. Hence, the torque and power output of the engine can be accurately measured [Atkins, 2009]. Direct coupling means that the dynamometer shaft is connected to the driveshaft or propeller shaft of the engine under test resulting both the engine and the dynamometer running at the same speed [Gitano, 2008a]. In addition, since the dynamometer rotor is coupled to the shaft, its speed is also identical to the speed of engine crankshaft [Atkins, 2009].

William Froude introduced the first modern dynamometer when he designed a dynamometer for HMS Conquest, a C-class light cruiser of the Royal Navy [Atkins, 2009]. Nowadays, there are many types of dynamometers used in the industry. Each of them has its own advantages and disadvantages over its counterparts. Commonly used dynamometers in the industry include [Gitano, 2008a]:

- Frictional (brake) dynamometer,
- Hydraulic (water brake) dynamometer,
- Eddy current dynamometer,
- Generator type dynamometer, and so forth.

2.2.1 Frictional (brake) dynamometer

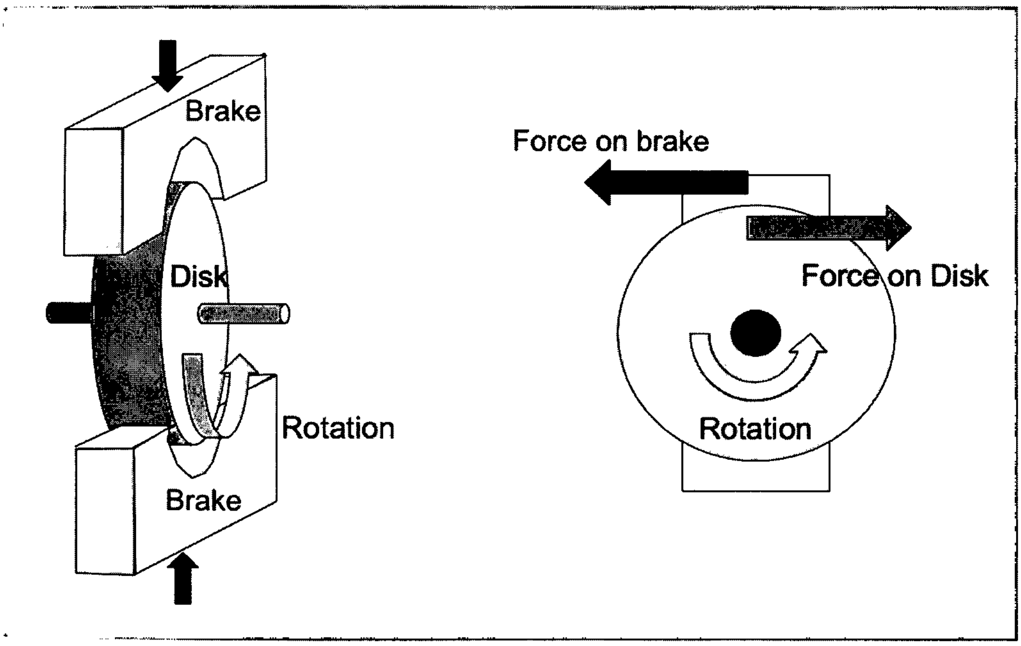


Figure 2.1 : Frictional dynamometer. [Gitano, 2008a]

Frictional (brake) or dry friction dynamometer is the oldest type of dynamometer. It contains mechanical braking device such as belt or frictional 'shoe' as shown in Figure 2.1. It operates with the shaft spins the disk or drum. The braking device then applies force to resist the rotating disc or shaft. The force applied by the brake is equal to the force on the disk and acts in the opposite direction.

2.2.2 Hydraulic (water brake) dynamometer

Hydraulic dynamometer is fundamentally a hydraulic pump. The engine rotates the shaft, which hereupon spins the impeller. Water is pumped from a reservoir through a hydraulic circuit via a throttling valve as shown in Figure 2.2. Hydraulic drag induced by the water resists the motion of the impeller. The load is varied through opening and closing of the valve. Hydraulic dynamometers typically have the highest power densities.

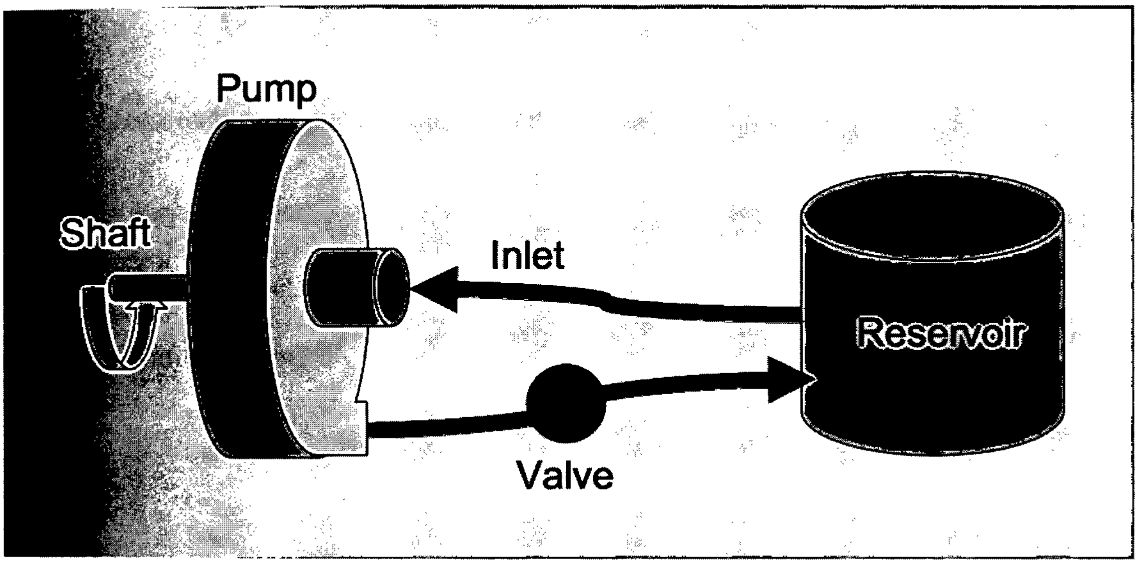


Figure 2.2 : Hydraulic dynamometer. [Gitano, 2008a]

2.2.3 Eddy current dynamometer

Eddy current dynamometer is an electromagnetic load device consists of a disk placed inside its housing. The coupling shaft spins the disk, which contains large electromagnetic coils as shown in Figure 2.3. This initiates electric current. As the current passes through the coils that surround the disk, a strong magnetic field is induced. The magnetic field creates a so-called 'eddy current' in the disk that resists its rotation. This produces a torque between the housing and the disk. Varying the current varies the torque generated as well as the load on the engine.

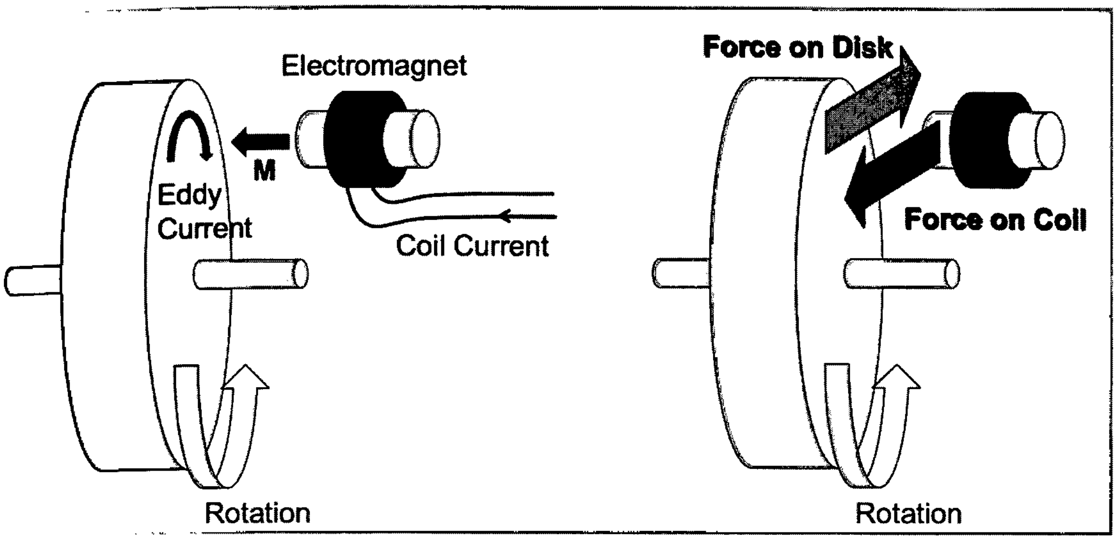


Figure 2.3 : Eddy current dynamometer. [Gitano, 2008a]

2.2.4 Generator type dynamometer

In a system comprising of generator type dynamometer, the coupling shaft spins the rotor of a generator as depicted in Figure 2.4. Electrical load is applied to the output of the generator creating an electromagnetic force.

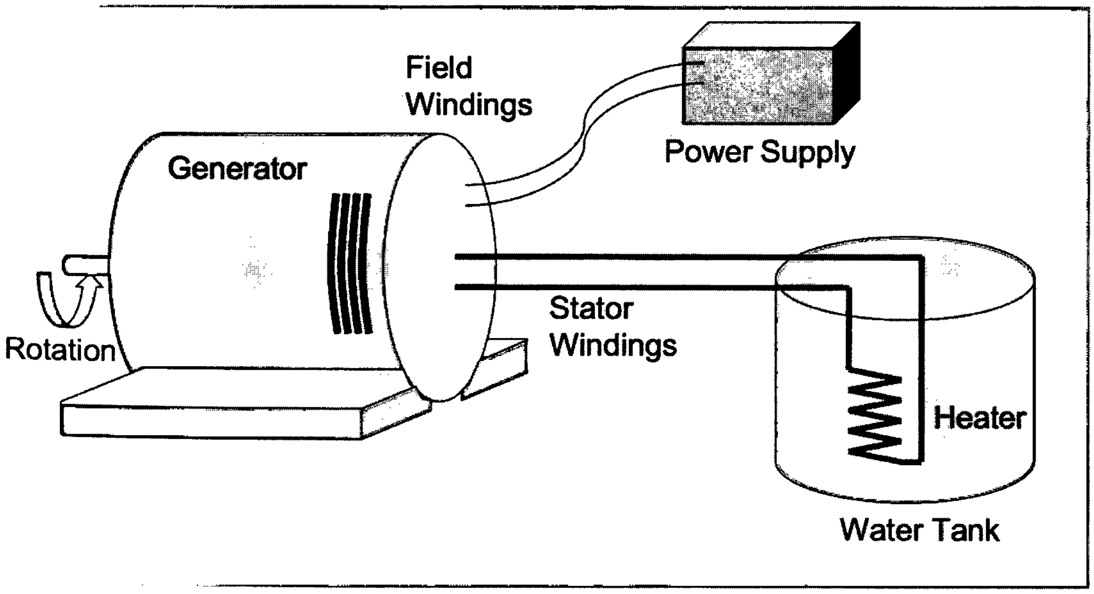


Figure 2.4 : Generator type dynamometer. [Gitano, 2008a]

This force resists the motion of the rotor. A resistor bank (heater) is commonly used as the load, which is either air or water-cooled. In order to vary the mechanical load, the field winding current is controlled.

2.2.5 Different types of dynamometer

In previous sections, four common dynamometers are described. Following table lists the advantages and disadvantages of different types of dynamometer. This table was reproduced from some literatures. [Crolla, 2009; Martyr & Plint, 2007a].

Table 2.1 : Pros and cons of different types of dynamometer. [Martyr & Plint, 2007a]

Dynamometer type	Advantages	Disadvantages
Froude sluice plate	Obsolete, but many cheap and reconditioned models in use worldwide, robust	Slow response to change in load. Manual control not easy to automate
Variable fill water brakes	Capable of medium speed load change, automated control, robust and tolerant of overload. Available for largest prime-movers	'Open' water system required. Can suffer from cavitation or corrosion damage
'Bolt-on' variable fill water brakes	Cheap and simple installation. Up to 1000 kW	Lower accuracy of measurement and control than fixed machines
Disc type hydraulic	Suitable for high speeds	Poor low speed performance
Hydrostatic	For special applications, provides four quadrant performance	Mechanically complex, noisy and expensive. System contains large volumes of high pressure oil
D.C. electrical motor	Mature technology. Four quadrant performance	High inertia, commutator may be fire and maintenance risk
Asynchronous motor (A.C.)	Lower inertia than DC. Four quadrant performance	Expensive. Large drive cabinet needs suitable housing
Permanent magnet motor	Lowest inertia, most dynamic four quadrants. Small size in cell	Expensive. Large drive cabinet needs suitable housing performance
Eddy current	Low inertia (disc type air gap). Well adapted to computer control. Mechanically simple	Vulnerable to poor cooling supply. Not suitable for sustained rapid changes in power (thermal cycling)

Friction brake	Special purpose applications for very high torques at low speed	Limited speed range
Air brake	Cheap. Very little support services needed	Noisy. Limited control accuracy
Hybrid	Possible cost advantage over sole electrical machine	Complexity of construction and control

In this study, the eddy current dynamometer is used throughout the analysis. Different results will be obtained, given that other type of dynamometer is used.

2.3 Operating mechanism of a dynamometer

The operation of a dynamometer can be simulated by a spring balance, anchored to the ground, with a rope attached to the top eye and wrapped around a drum with a slipknot as shown in Figure 2.5. As the drum rotates, the slipknot tightens, tensioning the rope. The tension is indicated as a weight by the spring balance.

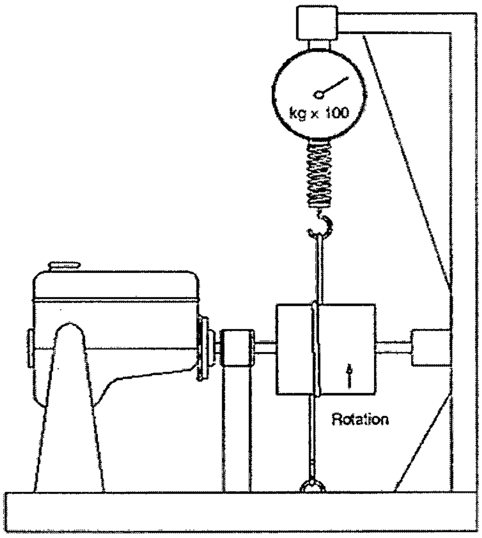


Figure 2.5 : Dynamometer operation simulated by a spring balance. [Atkins, 2009]

There is a friction between the rope and the drum, which slows down the motion of the drum and its driving engine until a certain speed, for example 'X' RPM, and the spring balance shows a reading of 'Y' kg. This shows that the weight lifted is 'Y' kg, and therefore the speed of the drum or the engine recorded is used to calculate the horsepower. In real application, the engine is clamped on a test bed with a drive shaft coupled to it. The other end of the drive shaft is coupled to the dynamometer, which replaces the system containing the drum and the spring balance as described previously [Atkins, 2009].

2.3.1 Principle of operation

The operating principle of a dynamometer is illustrated in Figure 2.6. Depending on the type of dynamometer, the rotor is coupled to a stator electromagnetically, hydraulically or by mechanical friction. The stator is supported in low-friction bearings. It is stationary balanced with the rotor via static calibration. By balancing it with weights, springs or pneumatic means, the torque exerted on it with the rotor turning can be measured [Atkins, 2009].

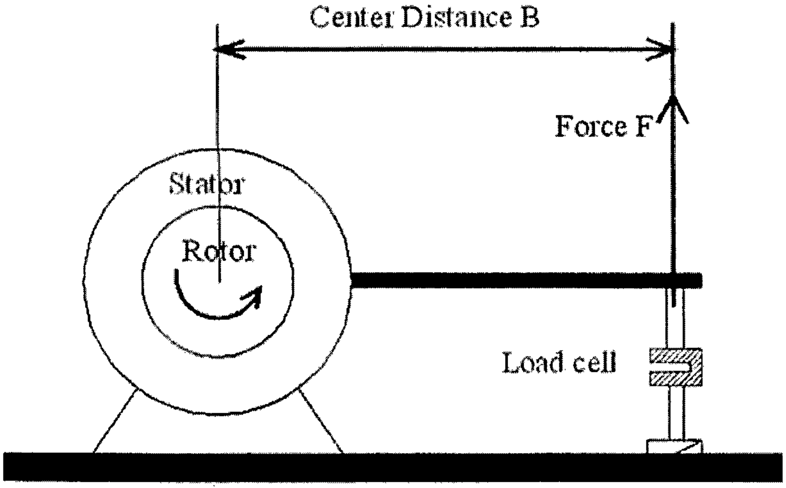


Figure 2.6 : The mechanism of torque measurement [Atkins, 2009].

Given that the torque T is exerted, then it can be calculated as follows:

$$T = FB \tag{2.1}$$

On the other hand, the power P generated by the engine under test is as the matter of fact the product of torque and angular speed as given by following equation:

$$P = 2\pi NT \tag{2.2}$$

where N is the engine speed in revolution per minute (RPM).

As previously mentioned, torque denotes the ability of an engine to do work, whereas power indicates the rate at which the work is done. The power calculated from Equation (2.2) is known as brake power, designated as P_b. This is the useful power delivered by the engine to the applied load. Basically, the dynamometer applies a resistive force to oppose the rotation of the drive shaft (or the torque of the engine's crankshaft). This causes the engine to work harder to retain its rotational speed.

2.3.2 Operating quadrants

Figure 2.7 depicts the four quadrants, which the dynamometer may be operated.

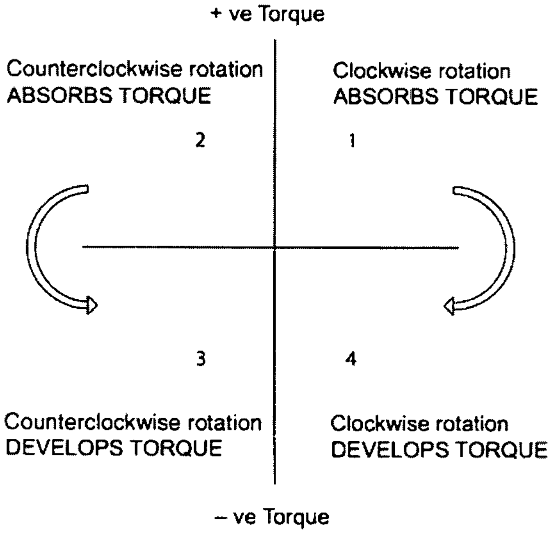


Figure 2.7 : Operating quadrants of a dynamometer. [Atkins, 2009]

In general, most of the engines testing takes place in the first quadrant with the engine running counter-clockwise if viewed from the flywheel end. All types of dynamometer are normally able to operate in the first or second quadrant [Atkins, 2009; Martyr & Plint, 2007a].

A dynamometer needs to operate in third and fourth quadrants when it is required to produce power as well as to absorb it. However, the choice is limited since only DC machines, AC machines, hydrostatic and hybrid dynamometers are able to operate in such quadrants. These dynamometers are reversible, thus able to operate in all four quadrants. An eddy-current dynamometer is also basically reversible. Nevertheless, a hydraulic dynamometer is normally designed for one directional rotation, albeit it could be operated in reverse at low fill state without damage.

In present, the transient testing (very rapid load changes and torque reversals) is growing resulting an increase in demands for four-quadrant operation. A notable feature of a four-quadrant dynamometer is its ability to start the engine. Table 2.2 lists some common types of dynamometer and their particular operating quadrant, which is reproduced from [Atkins, 2009].

Table 2.2 : List of dynamometers and their operating quadrants. [Atkins, 2009]

Type of Machine	**Operating Quadrant(s)**
Hydraulic sluice plate	1 or 2
Variable fill hydraulic	1 or 2
Hydrostatic	1, 2, 3, 4
DC electrical	1, 2, 3, 4
AC electrical	1, 2, 3, 4
Eddy current	1 and 2
Friction brake	1 and 2

2.4 Torsional vibration

2.4.1 Overview

A dynamometer-engine system can be considered as identical to a system comprises of two rotating masses connected by a flexible shaft as illustrated in Figure 2.8. Both masses possess a tendency to vibrate 180° out of phase about an arbitrary point located along the connecting shaft. The oscillatory movement is superimposed on any steady rotation of the shaft. Hence, such system tends to generate torsional vibrations [Martyr & Plint, 2007b]. The twisting of the shaft while the engine rotates is known as torsional vibration. It occurs due to the periodical nature of actuating torque [Meirelles et al., 2007]. Excessive amount of torsional vibration can bring about failures of the crankshaft, couplings, engine dampers and so forth [Feese & Hill, 2009].

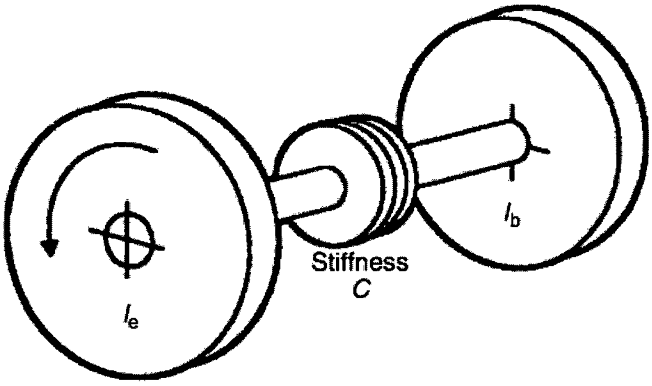


Figure 2.8 : Two mass system. [Martyr & Plint, 2007b]

2.4.2 Literature review

The importance of the knowledge and understanding of torsional vibration has led to publishing of many journals and articles regarding the subject. A method to predict the behaviour of the torsional vibrations in internal combustion engines at transient and steady state regime by the modal superposing method was developed in 1987 [Johnston & Shusto, 1987]. In some systems, excessive vibrations are exhibited on