# Chapter 1

# The Test Facility and Methods of Measuring Engine Power

## Test Facilities and Test Cells

To test an engine, we must be able to compare the performance of differing states of tune and different types of engines. To do this, a complex control and data acquisition system is required. Much detailed planning is needed before setting up such a facility. Requirements for complex test procedures to satisfy ever demanding regulations have elevated the status of an engine or vehicle test cell into that of a sophisticated laboratory. Such a laboratory is heavily dependent on advanced testing equipment and instruments. This apparatus requires equally sophisticated and, more importantly, reliable support services and utilities to maintain its reliability and to deliver the performances expected. Similarly, new and complicated test procedures require the strict control of various parameters such as temperature, pressure, flow, humidity, velocities, and so forth, all of which lie within narrow tolerance bands. Furthermore, test laboratories are required to comply with international and local legislation standards and governmental requirements such as the Health and Safety at Work Regulations (1999), Control of Substances Hazardous to Health (COSHH), building regulations, petroleum and fire officer requirements, ISO standards, and BS/BS EN standards (these being generic names given to a family of standards developed to provide a framework around which a quality management system can effectively be established).

Regardless of the purpose of the test to be conducted within a cell running any form of a test—be it a simple durability test or a complicated analytical test—the operation is an expensive exercise and thus must be accomplished correctly the first time with no failures or any form of interruption. Repeating a test unnecessarily even once due to any form of failure or interruption is expensive, time consuming, and, in some instances, could result in the loss of business due to unreliability.

The services that need to be installed in a test facility include such items as ventilation; treated air; cooling water; and conditioning systems for fuel, lubricant, coolant, and combustion air. Other items that also must be considered include compressed air; exhaust gas disposal; analytical, span, and other reference gases; lighting and emergency lighting; power and small power; control supplies; and detection, alarm, and suppression systems. In reality, the utilities are not limited to only those mentioned here but include the provision of acoustics, noise, and vibration measuring and monitoring equipment; fuel systems storage and distribution; gas systems storage; and utilities for the control rooms, operator areas, workshops, laboratories, offices, and so forth. It is truly a task for the professional.

The facility does not end with the test cell. A clean engine build area is required, as well as a pre-installation rig area, an instrumentation store, a fuel farm, a general parts store, a dirty strip and wash area, a study area for the engineers and technicians, and toilet and washing facilities. To ensure smooth operation of the facility, the total site must be planned in great detail. Figure 1.1 shows a specimen layout of such a facility, and Figure 1.2 shows a typical development facility.

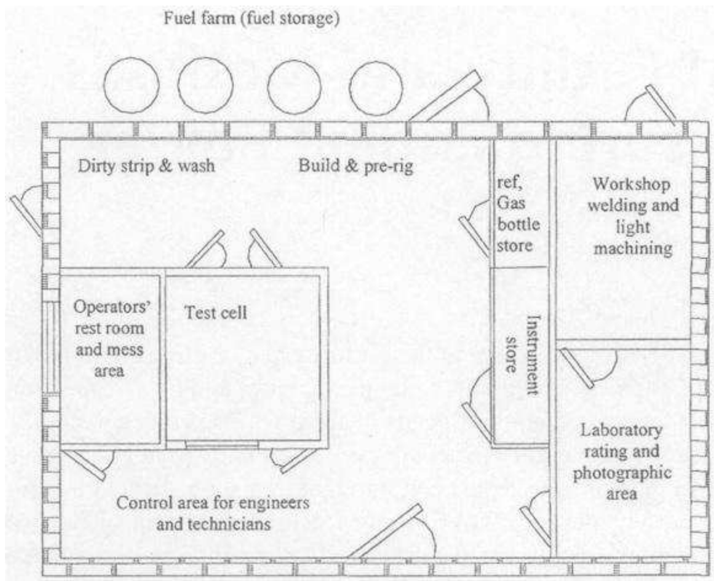


*Figure 1.1 A typical test facility layout.*

*Figure 1.2 A typical development facility. (Courtesy of Froude Hoffman)*

In designing the cell, the cooling plant and air exchange through the cell limit the size and power of the engines that can be tested. (Compared with the cost of the cooling plant and air exchange, the dynamometer is relatively inexpensive.) With this in view, the recommended action is to attempt to estimate the maximum power output that will need to be tested over the next 10 years and then add 50% to the capacity of the cooling and air-exchange systems. These systems can simply be throttled down, if required, to suit any specific application.

When setting out the specification of a new test facility, it is recommended that a series of energy balance calculations for a number of applications be undertaken. This work entails noting the fuel rate of the engine at maximum rated speed and load, taking into account the relative efficiency of the engine (for example, 26% for a typical gasoline application and 34% for a typical diesel-powered engine), then identifying where the remaining heat energy is lost: heat to exhaust, heat to coolant, heat to oil, radiated heat from the engine, and so forth. From this, one can review the amount of air circulation required within the cell. The air that the engine inducts is only a small part of the whole. A great deal of radiated heat must be dissipated, and this requires a significant airflow—up to five complete cell air changes per minute.

Referring to Figure 1.3, the energy balance of a 2.4-liter EURO 3 engine manufactured by the Andoria engine company in Poland is reviewed. This power unit produced 75 kW at the flywheel at a rated speed of 4100 rev/min. The specific fuel consumption at net peak torque (ISO 1585) was 255 g/kWh.

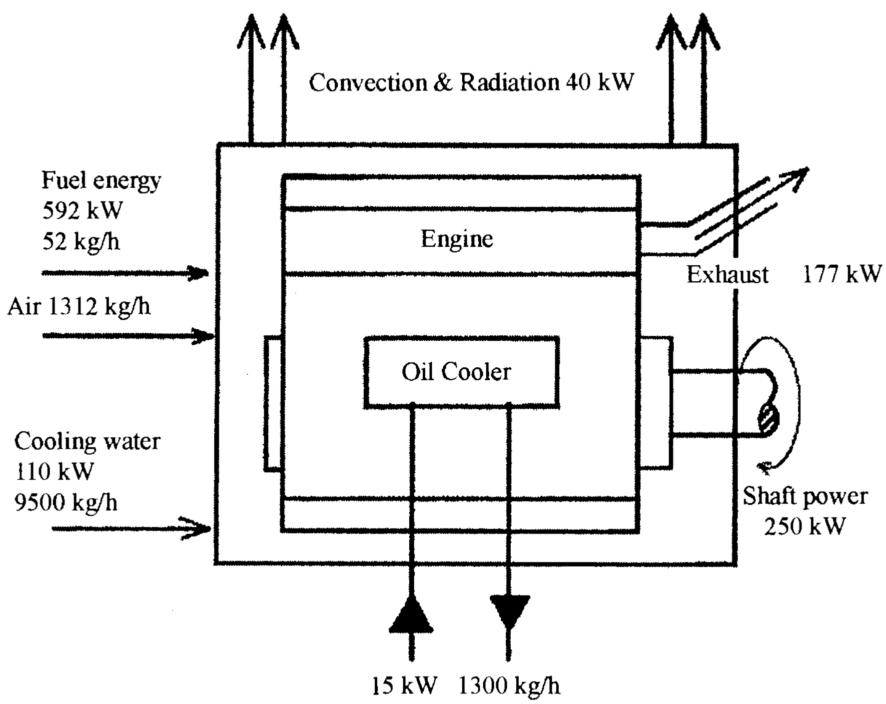


*Figure 1.3 Energy into the engine; energy out of the engine.*

$$\text{Brake specific fuel consumption} = \frac{\text{Fuel used (g/H)}}{\text{Power (kW)}}$$

$$255\ (\text{BSFC}) = \frac{\text{Fuel used}}{75\ \text{kW}}$$

$$\therefore\ \text{Fuel used (liters)} = 75 \times 0.255 = 19.125\ \text{kg/h}.$$

The fuel used with this specific fuel consumption calculates out at 19.125 kg/h. The specific gravity of this fuel was not known, but it would lie between 0.815 and 0.855 kg/liter. For the preceding calculations, the following were assumed:

$$\text{Fuel used} = 19.125 \times 0.815 = 15.58 \text{ liters}$$

$$3.8 \text{ liters of standard diesel} = 155 \times 10^6 \text{ joules} = 147{,}000 \text{ Btu}$$

$$1 \text{ kWh} = 3.6 \times 10^6 \text{ joules}$$

$$19.125 \text{ kg} = 15.58 \text{ liters} \times 40.79 \times 10^6 \text{ joules} = 176.53 \text{ kW}$$

Thus, the energy in is 176.53 kW, and the shaft energy out is 75 kW. (The remainder is shown in Figure 1.3.) Thus, it can be seen that this particular engine is 42.58% efficient (Figure 1.3).

The energy balance of the 75-kW turbocharged diesel engine described previously is shown in Table 1.1.

**TABLE 1.1**
**ENERGY BALANCE**

| Item | Energy In | Item | Energy Out |
|---|---|---|---|
| Fuel | 176.53 kW | Power | 75 kW |
| | | Heat to coolant | 33 kW |
| | | Heat to oil | 4.5 kW |
| | | Heat to exhaust | 53.1 kW |
| | | Convection and radiation | 11 kW |
| Total | 176.53 kW | Total | 176.53 kW |

When designing a test cell, consider all the heat-generating surfaces, such as those shown in Figure 1.4.

## Dynamometers

William Froude (Figure 1.5) is regarded as the father of the modern dynamometer. His first project was to design a dynamometer for the steam engine in the *HMS Conquest* (Figures 1.6 through 1.9). The unit was fitted to the propeller shaft of the *HMS Conquest*, and the unit was submerged to provide cooling capacity for the absorbed power. Handles located on the stern of the ship operated a complex series of bevel gears that opened and closed sluice gates. An arrangement of levers read the torque on a spring balance located on the quay; a mechanical mechanism noted the engine revolutions. These were coupled to a rotating drum, and this produced a speed-versus-load chart, the area under the graph being the power.

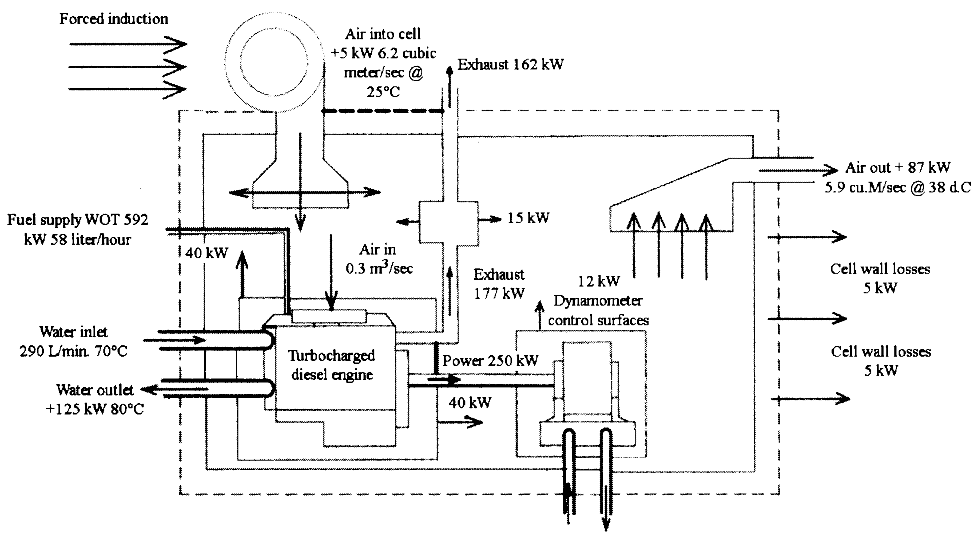


*Figure 1.4 Typical test cell energy balance.*

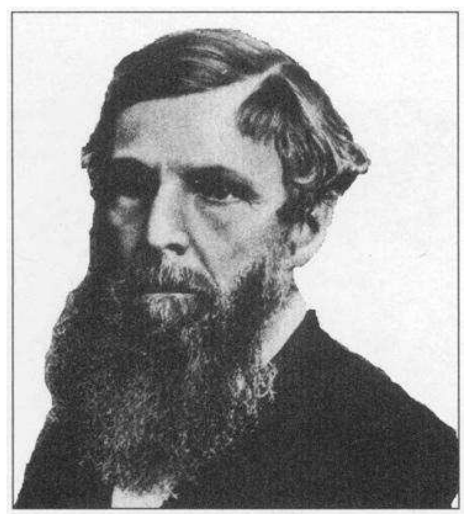

*Figure 1.5 William Froude. (Courtesy of Froude Hoffman)*

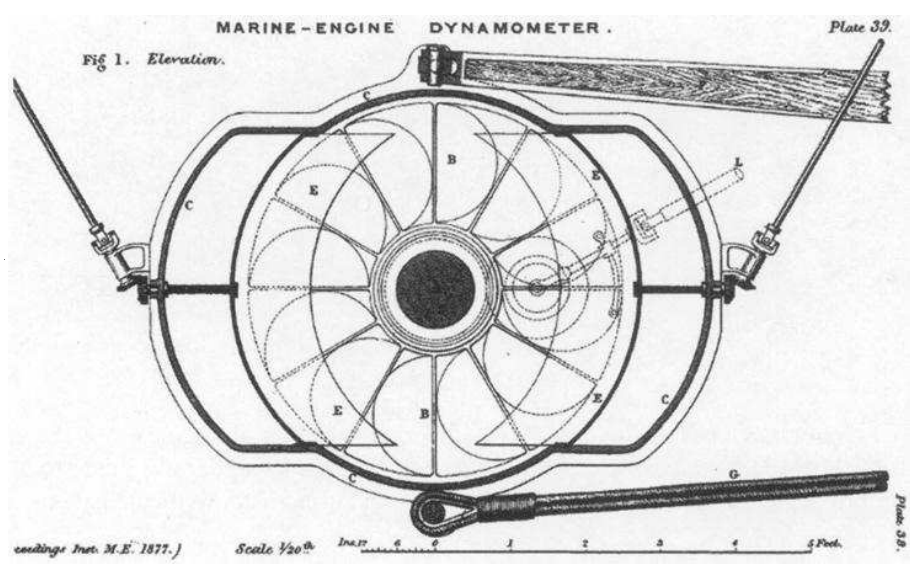


*Figure 1.6 Original dynamometer drawing. (First published by the Institute of Mechanical Engineers in 1877)*

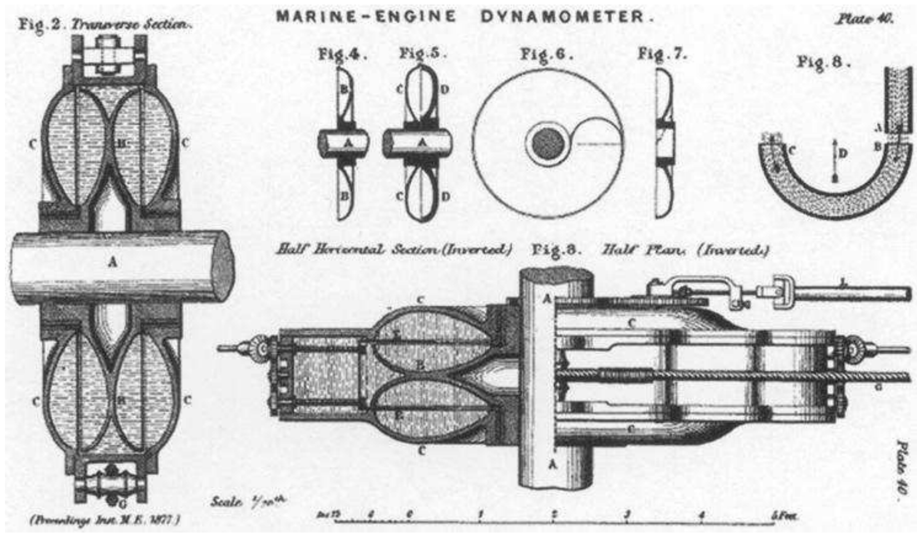


*Figure 1.7 Original drawing, section of the rotor. (First published by the Institute of Mechanical Engineers in 1877)*

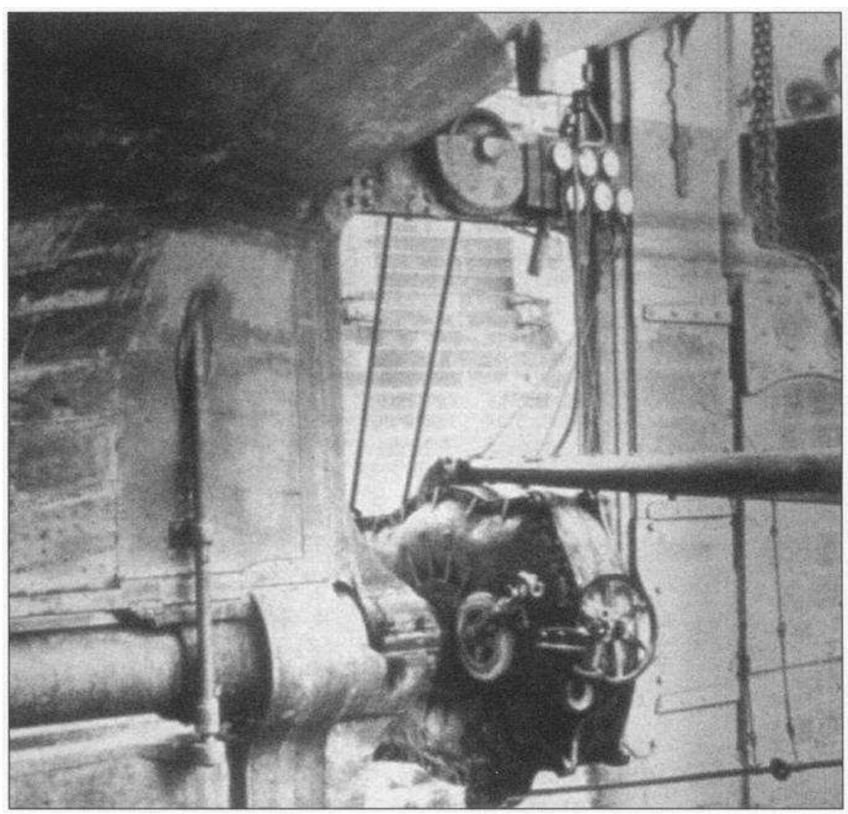

*Figure 1.8 Submerged original dynamometer. (Courtesy of Froude Hoffman)*

The dynamometer is as fundamental to the in-cell testing of engines as is the engine. In establishing the engine characteristics and performance under different "road load" conditions, it is necessary to be able to safely and effectively replicate actual on-road

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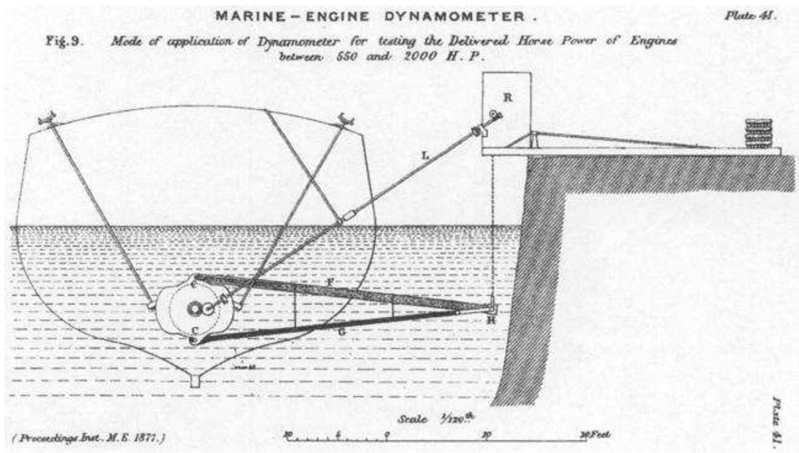


*Figure 1.9 Original installation drawing. (First published by the Institute of Mechanical Engineers in 1877)*

conditions on a consistent and repeatable basis. This is in essence what the dynamometer enables one to do when running engines are tested.

## Function of the Dynamometer

The function of the dynamometer is to impose variable loading conditions on the engine under test, across the range of engine speeds and durations, thereby enabling the accurate measurement of the torque and power output of the engine.

## How the Dynamometer Works

To better understand how the dynamometer works, imagine anchoring a spring balance to the ground, with a rope attached to the top eye and wrapped around a drum with a slipknot. The slipknot is tightened as the drum rotates, the rope then will be tensioned, and the balance will extend to indicate this tension as a weight (Figure 1.10).

Friction between the rope and the drum will slow the drum and its driving engine until, for example, at 1000 rev/min, the spring balance reads 210 kg. In effect, the weight being lifted is 210 kg, and the speed of the drum or engine then will be used in a formula to calculate the horsepower. In its simplest form, the engine is clamped on a test bed frame, and the output from the engine flywheel is connected to a driveshaft (propeller shaft) and hence a dynamometer.

## Dynamometer Types and Operating Principles

Many types of dynamometers are available to the industry, with each having its own distinct advantages and disadvantages compared to those of its rivals. This section will focus on the main types found across the industry in general and will give only a brief outline of the other not-as-commonly-used variants. The main types of dynamometers considered here are as follows:

- "Hydraulic" (or water brake), of which there are two types:

  1. Constant fill
  2. Variable fill

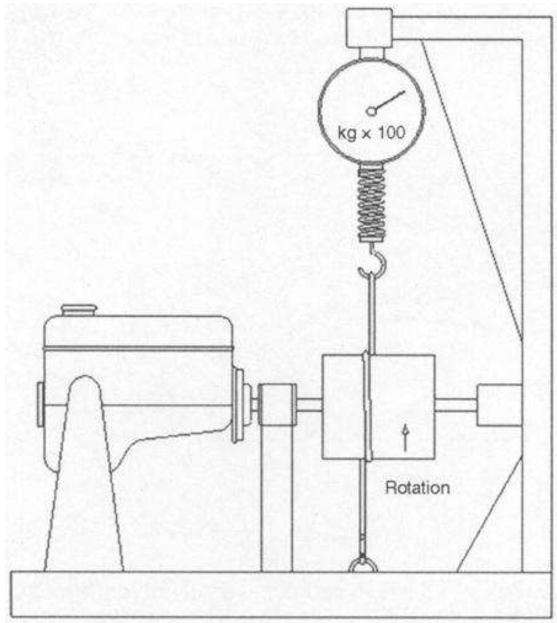


*Figure 1.10 Friction rope dynamometer.*

- Electrical, of which there are three main types:

1. DC current
2. AC current
3. Eddy current

For many years, the design principle of the Froude dynamometer (Figures 1.6 to 1.9) was regarded as the industry standard dynamometer. While high-resolution transient systems are much favored today, an understanding of the design principles of these early hydraulic dynamometers is worthwhile. These dynamometers ranged in absorption values from 1 kW to more than 10,000 kW. In Figure 1.11, the rotor pockets and driveshaft of an ultra-large unit can be seen clearly. The water in the stationary pockets that is shearing those in the rotor pockets produces the torque reaction and the power absorption action.

Although the hydraulic dynamometer is based on a design that is more than 130 years old, it is still used in many applications, including the testing of Formula 1 engines and gas turbine aircraft engines.

The hydraulic water brake used in Formula 1 race engines will absorb more than 1000 BHP at speeds of greater than 20,000 rev/min (Figure 1.12).

The rotor is a critical design feature when running at very high speeds (greater than 20,000 rev/min). The example shown in Figure 1.13 has a diameter of 154 mm. This allows for a safety factor that is established by the bursting speed of the rotor. Unlike the grooves on either side of the rotor, these are labyrinth grooves and act as a noncontact seal.

From Figure 1.14, it can be seen that the main shaft is carried by bearings fixed in the casing. The casing in turn is carried by anti-friction trunnions, so that it is free to swivel about the same axis as the main shaft. When on test, the engine is coupled directly to the main shaft transmitting the power to a rotor revolving inside the casing. This

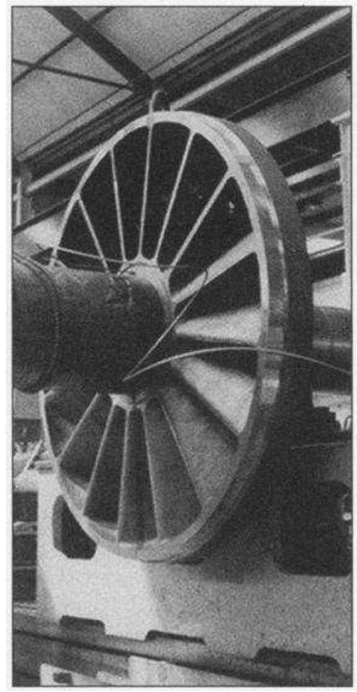

*Figure 1.11 Rotor pockets. (Courtesy of Froude Hoffman)*

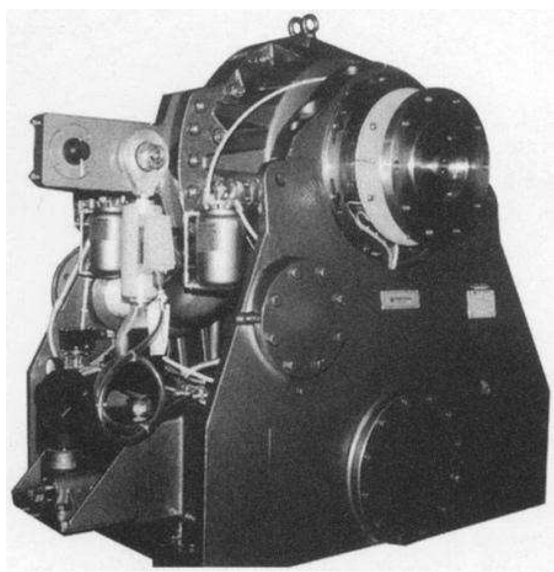

*Figure 1.12 High-performance F-type water brake. (Courtesy of Froude Hoffman)*

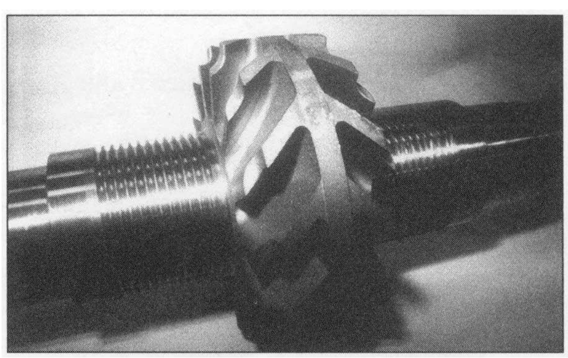

*Figure 1.13 High-performance rotor. (Courtesy of Froude Hoffman)*

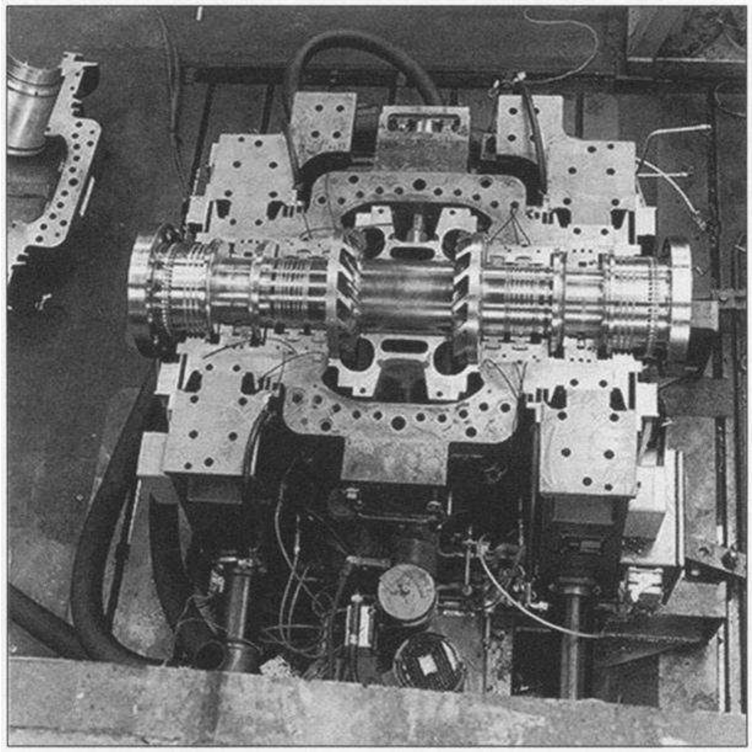

*Figure 1.14 Eddy current unit. (Courtesy of Froude Hoffman)*

water is circulated to provide hydraulic resistance while simultaneously carrying away the heat developed by the destruction of power. In each face of the rotor are formed pockets of semi-elliptical cross sections divided from one another by means of oblique vanes (Figure 1.11).

The internal faces of the casing are provided with liners, which are pocketed in the same way. Thus, the pockets in rotors and liners together form elliptical receptacles around which the water moves at high speed. Where high torque absorption levels are required, twin rotor units are specified (Figure 1.14). When in action, the rotor discharges water at high speed from its periphery into pockets formed in the casing liners, by which it then is returned at diminished speed into the rotor pockets at a point near the shaft. The resistance offered by the water to the motion of the rotor reacts upon the casing, which tends to turn on its anti-friction roller supports. This tendency is counteracted by means of a lever arm terminating in a weighing device that measures the torque.

The forces resisting rotation of the dynamometer shaft may be divided into three main classes:

1. The hydraulic resistance created by the rotor
2. The friction of the shaft bearings, which usually are of the ball type
3. The friction of the sealing glands

Note that every one of these forces reacts upon the casing, which, being free to swivel upon anti-friction trunnions, transmits the whole of the forces to the weighing apparatus. "Every force resisting rotation of the engine shaft is caused to react upon the weighing apparatus."

The dynamometer shaft is of robust construction with very high torque absorption characteristics. These are required to cope with the demands of resisting the rotational force (or torque) of the engine power unit to which it is coupled by the prop shaft/driveshaft.

The dynamometer shaft is connected to the driveshaft (or prop shaft), which in turn is bolted to the engine crankshaft. This means that the engine crankshaft and the dynamometer shaft will be running at the same speed (revolutions per minute [rpm]). This again means that as the rotor is connected to the dynamometer shaft, the rotor is driven at the same speed as the engine crankshaft.

The quantity of water required to carry away the heat generated by the absorption of power can be calculated. Each kilowatt that is absorbed generates 14,338 calories per minute, most of which passes into the cooling water.

## *Operating the Dynamometer*

Prior to starting the engine, open the inlet valve fully and the outlet valve very slightly. It is almost always advisable to start up with a light load, and this may be accomplished by screwing the sluice gates as far into the dynamometer as they will go. The engine is now started. To regulate the load, open the sluice gates by means of the handwheel, simultaneously operating the engine throttle, until the desired load and speed are obtained. Adjust the outlet valve to pass sufficient water to keep the temperature at a reasonable figure of 60°C. When running very light loads (e.g., the lower worldwide mapping points [15 BMEP psi at 1500 rev/min crank] with the sluice gates fully closed), a further reduction in load may be obtained by opening the outlet valve and gradually closing the water inlet valve.

## *Hydraulic Water Brakes*

There are two types of hydraulic water brakes: (1) the constant fill type, and (2) the variable fill type.

### Constant Fill Hydraulic Water Brakes

This type uses thin sluice plates inserted between the rotor and the stator, across the mouth of the pockets, to interrupt and affect the development of the toroidal (or whirlpool effect) flow patterns within the pockets. These sluice plates can be inserted to infinitely varying degrees to provide variable control of the loading of the engine crankshaft.

### Variable Fill Hydraulic Water Brakes

As the name suggests, this method relies on controlling the amount of water available within the dynamometer casing, thus affecting the water supply available to the rotor/stator assembly. This in turn will have an effect on the developed resistance force. The use of water outlet valves in varying the water flow through the dynamometer casing replaces the sluice plate control found in the constant fill machines.

A question arises here: Why is it that the flat-out maximum speed engine does not generate a resistant force in the dynamometer that is large enough to stall the engine? In some cases, it may indeed be possible to stall the engine with a high enough rating of dynamometer in good condition; however, this is not necessarily a desirable feature and is dangerous and damaging to both the engine and the dynamometer. When dynamometers reach this sort of range, damaging cavitation and erosion of the internal components can occur, particularly on the rotor and stator pocket faces. To prevent this, a means of controlling the resistance of the dynamometer to the torque generated by the engine is necessary. This controlling mechanism is the primary difference between the two types of water brake dynamometers.

Water brakes, as they are known, generally are being phased out in favor of electric dynamometers for their greater sensitivity of control. However, some remain in use, and they are helpful in developing the technician's understanding of engine loading for test purposes.

## *Electric Dynamometers*

The two main types of electric dynamometers are the eddy current dynamometer and the AC or DC transient dynamometer (generator dynamometer). This section on electric dynamometers will focus on the eddy current type of dynamometer (Figures 1.15 through 1.17), with some comment on the use and limitation of the other electric dynamometers.

### How the Eddy Current Dynamometer Works

With the eddy current dynamometer, the engine turns on the driveshaft, which is mounted on the rotor within the dynamometer casing. The outer edges of the rotor disc run between electromagnetic poles of the stator. Varying the excitations of these magnets, thereby altering their effect on the spinning rotor disc, will develop a resistant force or drag to counter the torque of the engine. Electromagnetic devices such as this are infinitely variable and have the added advantage of almost instantaneous implementation, thus giving greater control for the test-bed controller. Water cooling is achieved by passing

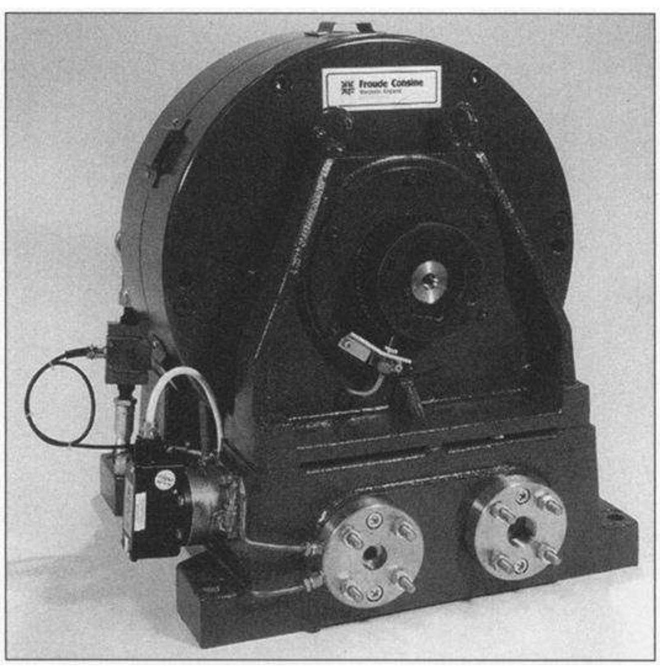

*Figure 1.15 An eddy current unit. (Courtesy of Froude Hoffman)*

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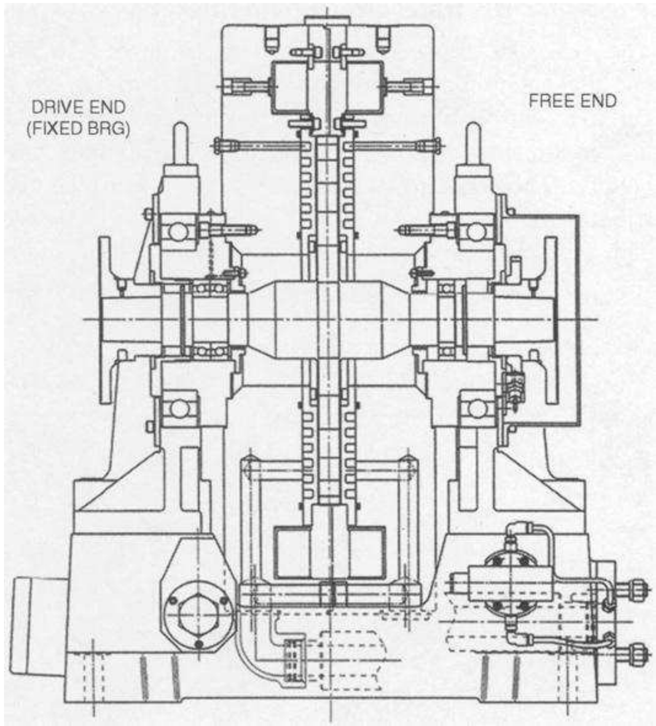


*Figure 1.16 Drawing of an eddy current dynamometer. (Courtesy of Froude Hoffman)*

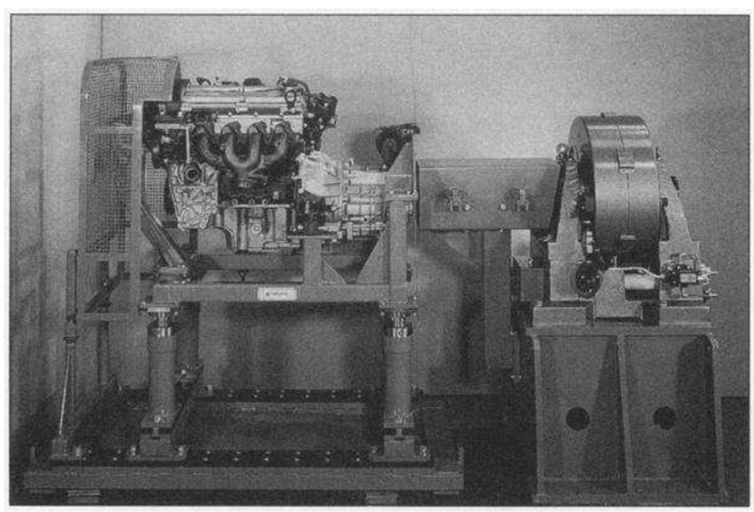

*Figure 1.17 An eddy current dynamometer installation. (Courtesy of Froude Hoffman)*

raw water into the cavities in the stator near the point where the rotor and the stator are closest (i.e., where the magnets act upon the rotor plate). Eddy current dynamometers are the most popular type used within the test cell environment. These vary in size and application, depending on the power/torque output of the engine being run. Special care must be given to the elimination of vibration when using electric dynamometers because the sensitivity of the control will be affected.

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### The AC or DC Transient Dynamometer

The AC or DC transient dynamometer (Figures 1.18 and 1.19) consists of a variable speed generator or alternator, the electrical output of which is delivered outside the test cell to a controllable load bank. In certain cases, particularly where large power output and continuous operation are concerned, the output may be delivered into the mains supply. The generator cooling air is drawn from the test cell and returned to it, contributing to the total heat release in the cell. No water cooling is likely to be involved. This type also can be used for motoring the engine and is used primarily for transient testing. Here, the aim is to evaluate fuel consumption variances (among other values),

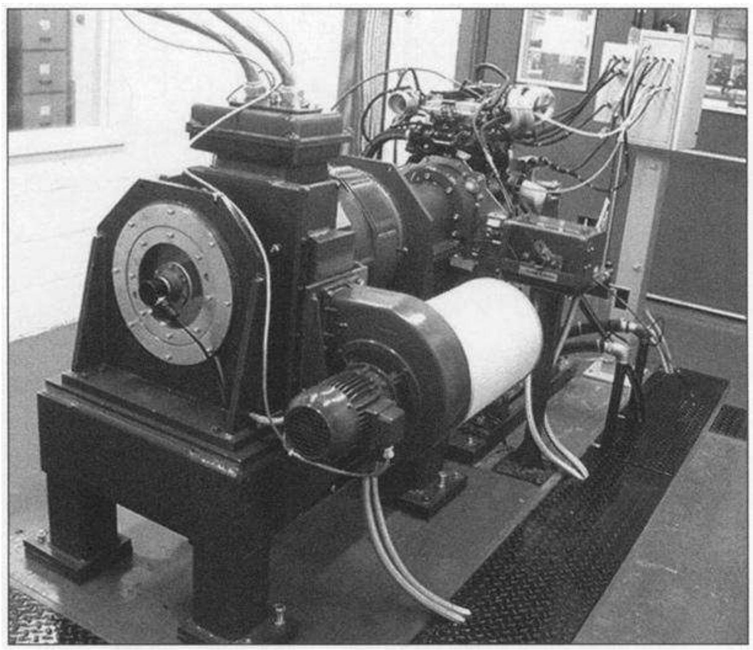

*Figure 1.18 A 130-kW AC dynamometer. (Courtesy of Froude Hoffman)*

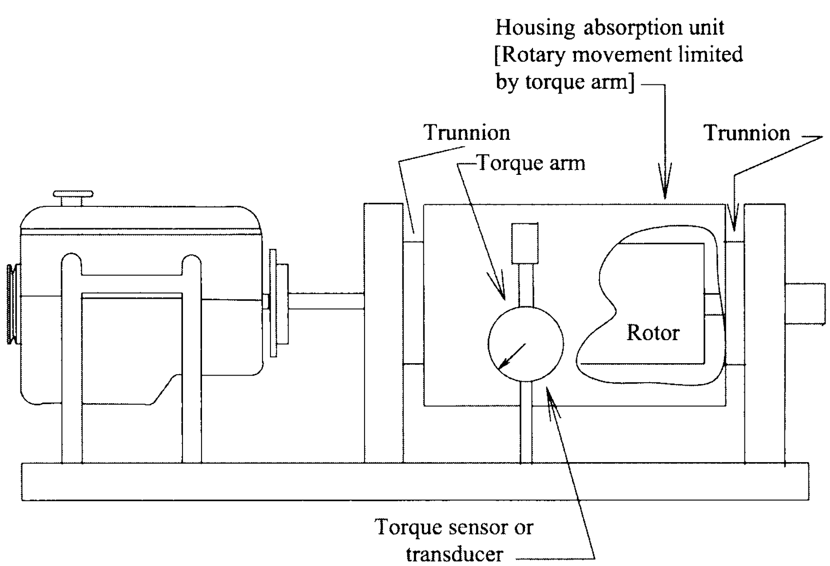


*Figure 1.19 A transient dynamometer.*

during split-second operations such as gear changing and overrun situations, which also affect fuel use and so forth, via the engine management systems.

Dynamometers must be kept within their specified calibration schedules because the accuracy of the dynamometers form the basis upon which all other data are generated and referenced. Dynamometer calibration information should be displayed where the test technician and the engineer can see it; this gives confidence to all, including the client's representatives, that best practices are being followed. Calibration usually is carried out by support technicians and involves the use of known mass weights placed on a specific-length calibration arm.

## Mechanism of the Dynamometer

Figure 1.20 illustrates the operating principle of the dynamometer.

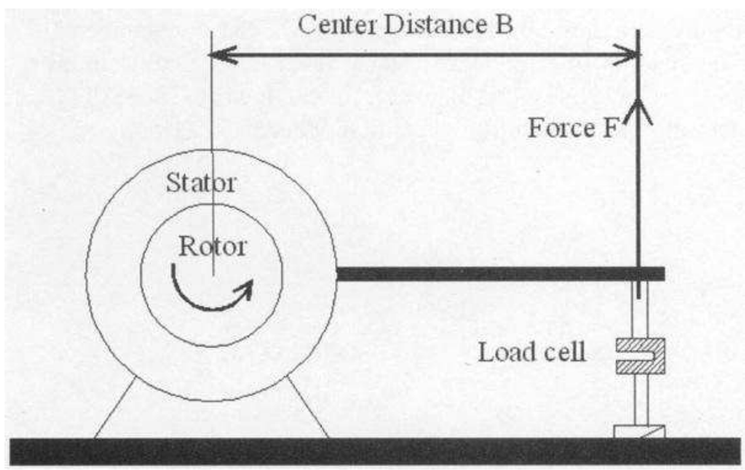


*Figure 1.20 Torque measurement.*

The rotor is coupled electromagnetically, hydraulically, or by mechanical friction to a stator that is supported in low-friction bearings. The stator is balanced with the rotor stationary (static calibration). The torque exerted on the stator with the rotor turning is measured by balancing the stator with weights, springs, or pneumatic means.

If the torque generated by the engine is T, then

$$T = Fb$$

The power P delivered by the engine and absorbed by the dynamometer is the product of torque and angular speed as

$$P = 2\pi NT$$

where N is the crankshaft rotational speed. In SI units,

$$P(\text{kW}) = 2\pi N(\text{rev/sec}) \times T(\text{Nm}) \times 10^3$$

or in U.S. units,

$$P(\text{hp}) = \frac{N(\text{rev/min}) \times T(\text{lbf} \cdot \text{ft})}{5252}$$

Note that torque is a measure of the ability of an engine to do work; power is the rate at which the work is done. The value of engine power as described here is called brake power, Pb. This power is the usable power delivered by the engine to the imposed load (i.e., brake power).

In essence, the dynamometer sets up a resistance to the rotating force (or torque) of the engine crankshaft. This resistance, in effect, is applying a load on the engine, making it work harder to maintain its rotational speed.

Let us now examine the dynamometer in greater depth and undertake a study of the performance or absorption curves of the differing types of dynamometer.

Figure 1.21 shows the four quadrants in which a dynamometer may be called to operate. The majority of engine testing takes place in the first quadrant with the engine running counterclockwise when viewed from the flywheel end. All types of dynamometers are naturally designed to run in the first or second quadrant.

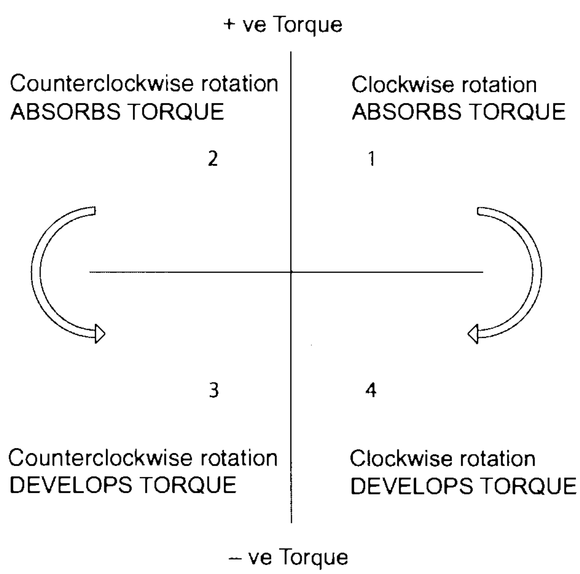


*Figure 1.21 Dynamometer operating quadrants.*

Table 1.2 shows a summary of the operating quadrants. Hydraulic dynamometers are designed in the main to run in only one direction, but they can be run in reverse without damage. As the name suggests, this method relies on controlling the amount of water available within the dynamometer casing, thus affecting the water supply available to the rotor/stator assembly. This in turn will have an effect on the developed resistance force. The use of water outlet valves to vary the water flow through the dynamometer casing replaces the sluice plate control found in the constant fill machines.

**TABLE 1.2**
**SUMMARY OF OPERATING QUADRANTS**

| 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 |

## Dynamometer Characteristics

Figures 1.22, 1.23, and 1.24 show the characteristics of hydraulic, eddy current, and AC or DC dynamometers, respectively.

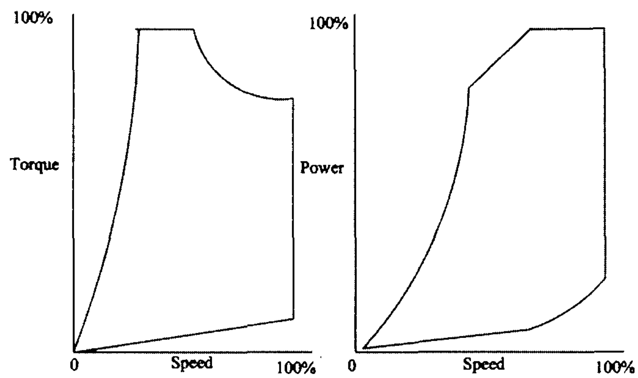


*Figure 1.22 Hydraulic dynamometer absorption curve.*

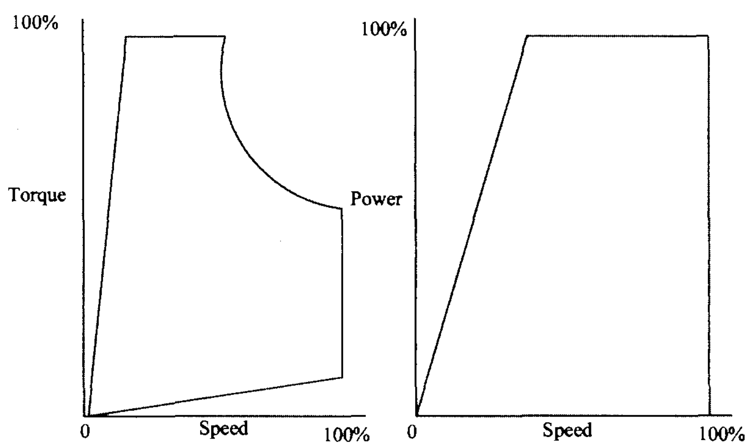


*Figure 1.23 Eddy current dynamometer. (Courtesy of Froude Hoffman)*

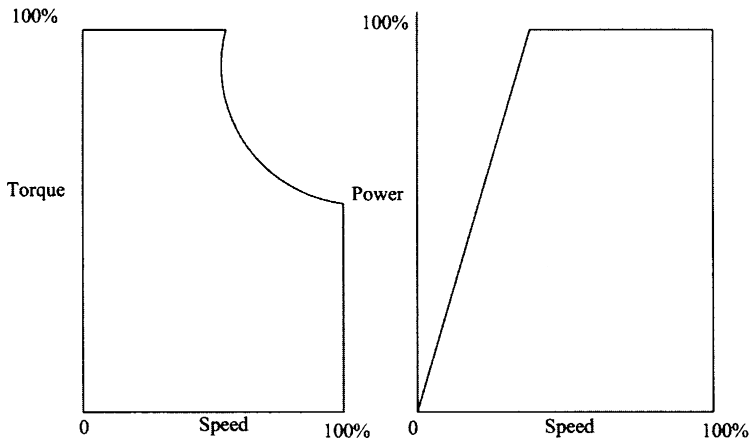


*Figure 1.24 AC/DC transient dynamometer absorption curve.*

The characteristics of the hydraulic dynamometer are as follows:

(a) Full maximum water. Torque increases with the square of the speed. No torque at rest.

(b) Performance limited by maximum permitted shaft torque.

(c) Performance limited by maximum permitted power, which is a function of cooling water throughput and its maximum permitted temperature rise.

(d) Maximum permitted speed.

(e) Minimum torque corresponding to minimum permitted water flow.

Figure 1.25 shows a general arrangement of the classic DPX hydraulic water brake.

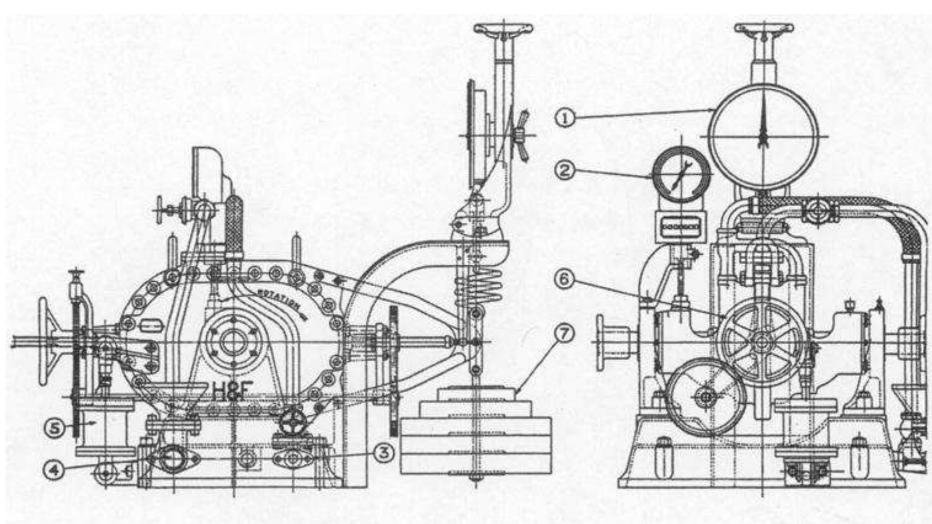


*Figure 1.25 DPX hydraulic water brake arrangement. (Courtesy of Froude Hoffman)*

The following are characteristics of the eddy current dynamometer:

(a) Low-speed torque corresponding to maximum permitted excitation.

(b) Performance limited by maximum permitted shaft torque.

(c) Performance limited by maximum permitted power, which is a function of cooling water throughput and maximum permitted temperature rise.

(d) Maximum permitted speed.

(e) Minimum torque corresponding to residual magnetization, windage, and friction.

The following are characteristics of the AC or DC transient dynamometer:

(a) Constant torque corresponding to maximum current and excitation.

(b) Performance limited by maximum permitted power output of the machine.

(c) Maximum permitted speed.

These performance curves are known as absorption or dynamometer envelopes.

The engineer will use this data when selecting a dynamometer for specific engine performance. For performance development, when best possible accuracy is required, then it is desirable to choose the smallest machine that will cope with the largest engine to be tested. For durability and validation work, it is best to select a machine that is rated approximately 50% above the maximum rated power of the engine in question.

## Selection of Prop Shafts

In general, dynamometer shafts are not designed to withstand heavy bending moments, which can be caused by the use of heavy couplings or by misalignment between the dynamometer and the engine. For this reason, flexible couplings should be used of the lightest possible construction and in perfect dynamic balance. Cardan shaft or hook joint shafts frequently are a favored choice of automotive test engineers, preferably with a universal joint at each end of the shaft designed to run out by 2 to 4° to stop brinelling of the roller bearings in the joint cruciforms (Figure 1.26).

In the absence of a cardan shaft, alignment between the engine and dynamometer must be carried out with a high degree of accuracy. However, remember that the engine mounts will tend to move and settle after the initial installation, and the alignment will need to be checked regularly over the first few days of testing. Poor attention to prop shaft selection and installation are potentially dangerous to test cell personnel due to the high speeds and high inertia forces.

Suitability of a coupling should include the following considerations:

1. The ability to handle the peak instantaneous cyclical torque due to the engine under consideration.

2. The effect of the torsional stiffness of the coupling proposed, usually as a result of natural torsional frequencies of the installation in which the coupling is fitted.

3. The effect of the considerations in items 1 and 2 on the amount of heat generated in the coupling. This is of particular importance when rubber in shear or in direct tension or compression type couplings are considered.

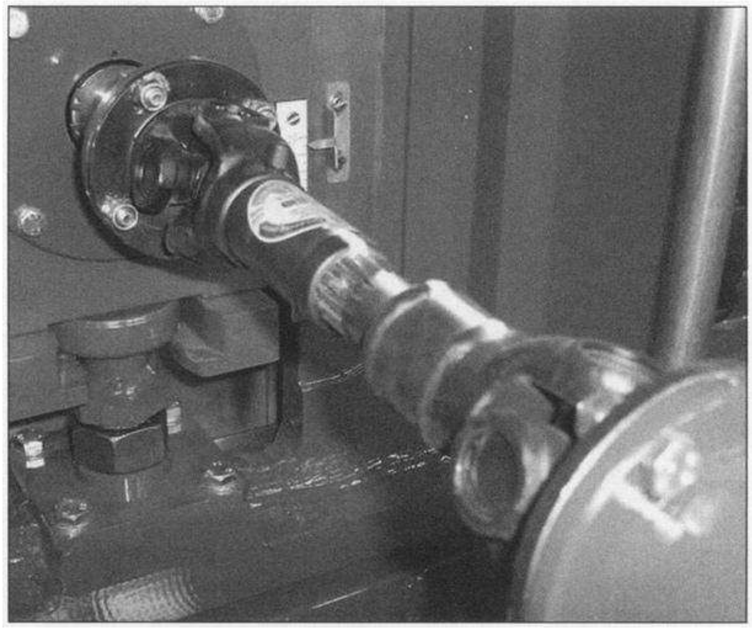

*Figure 1.26 Example of a hook joint cardan shaft. (Courtesy of University of Sussex)*

4. The effect of the coupling so far selected on the whirling characteristics of the whole coupling shaft.

5. Possible detrimental effects due to the inability of the coupling to deal with reasonable run out. The effect of the coupling so far selected on the whirling characteristics of the whole coupling misalignment or, in certain cases, the effect of end loading produced as a direct result of torsional twist on the bearings and so forth of the engine and dynamometer.

Practical experience shows that successful operation of test bed couplings requires the cooperation of all personnel involved. The selection of appropriate couplings for a given installation is important; however, for example, the machinist must take care that the correct depth and diameter are provided for any spigot fits. Installation fitters must conform to the degree of alignment required between the engine and the dynamometer shaft. It must be ensured that the correct bolts are fitted and that they are tightened appropriately to the required torque. In addition, there are always critical frequencies that should be avoided: the test personnel must not run at barred speeds for prolonged periods.

It is wise to always fit a robust safety containment guard should there be an unforeseen catastrophic coupling failure, for the kinetic energy in a swirling broken propeller shaft is immense.