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23 Measurement of Power

23.1 Introduction

Power is the rate at which work is performed. In the steam age, power measurements allowed engineers to compare engines, evaluate operating performance, and determine whether a machine was producing the work expected of it.

Today power is commonly measured in watts or kilowatts, but during the development of the steam engine a more practical unit was required. Early engines were intended to replace horses in mines, mills, and pumping stations. As a result, engineers naturally compared the work produced by an engine to the work that could be performed by a horse.

One of the earliest references to this comparison appears in the writings of Thomas Savery, who promoted his early steam-powered pumping engine as a replacement for teams of horses.

> “So that an engine which will raise as much water as two horses, working together at one time in such a work, can do, and for which there must be constantly kept ten or twelve horses for doing the same. Then I say, such an engine may be made large enough to do the work required in employing eight, ten, fifteen, or twenty horses to be constantly maintained and kept for doing such a work.”
>
> — Thomas Savery, 1702

The concept was later refined by James Watt, who sought a practical and consistent way of comparing steam engines with the horses they replaced. His work eventually led to the unit known as horsepower, which remained the standard measure of engine output for more than a century.

The comparison was not accidental. Both Savery and Watt were concerned with the problem of removing water from coal mines, where horses were widely used to power pumps and other machinery. The "horses" being replaced were often the pit ponies and draft animals that worked in and around the mines. Mine owners understood the cost of feeding and maintaining a team of horses, so describing an engine in terms of the number of horses it could replace provided a practical and easily understood measure of its value.

When Watt began marketing his engines, he formalized this comparison by defining a standard unit of power based on the work that could be performed by a horse. This became known as the horsepower.

Watt defined one mechanical horsepower as the ability to perform 33,000 foot-pounds of work per minute, or 550 foot-pounds of work per second.

A 1-horsepower engine can therefore:

- Raise 33,000 pounds through a height of one foot in one minute.
- Raise 330 pounds through a height of 100 feet in one minute.
- Perform any equivalent amount of work at the same rate.

Mathematically:

$$1\,\mathrm{hp} = 550\,\frac{\mathrm{ft{\cdot}lb}}{\mathrm{s}}$$

or

$$1\,\mathrm{hp} = 33000\,\frac{\mathrm{ft{\cdot}lb}}{\mathrm{min}}$$

23.2 When is a Horsepower not a Horse

The term *horsepower* is often used as though it were a single, precisely defined quantity. In practice, several different definitions have been used depending upon what is being measured.

Steam engineers therefore need to be careful when discussing horsepower ratings, since two machines with the same horsepower figure may not be referring to the same measurement.

Other horsepower definitions include:

- **Electric horsepower**: equivalent to 746 watts of electrical power.
- **Boiler horsepower**: a rating of a boiler's ability to generate steam.
- **Indicated horsepower (IHP)**: power developed within the engine cylinders.
- **Brake horsepower (BHP)**: power available at the engine shaft.
- **Drawbar horsepower (DBHP)**: useful pulling power available at the drawbar of a locomotive or traction engine.

The horsepower defined by Watt is now known as **mechanical horsepower**. Over time, engineers developed additional horsepower ratings for specific purposes, each measuring a different aspect of engine or boiler performance.

23.2.1 How Much Power Is a Horsepower?

The term *horsepower* suggests the power produced by a single horse, but the reality is more complicated.

Field experience showed that tasks such as plowing often required teams of several horses. The actual power available from a horse depends upon its size, conditioning, duration of work, ground conditions, and many other factors.

For this reason, James Watt's horsepower should not be regarded as the measured output of a particular horse. Rather, it is a standard unit of power that allows machines and animals to be compared using a common scale.

In practice, the useful measure is often not the number of horses, but the amount of work that can be performed. A farmer might ask how many plow bottoms can be pulled through a field, while a locomotive engineer might ask how many tons can be hauled up a grade. Such questions lead naturally to the concept of drawbar horsepower.

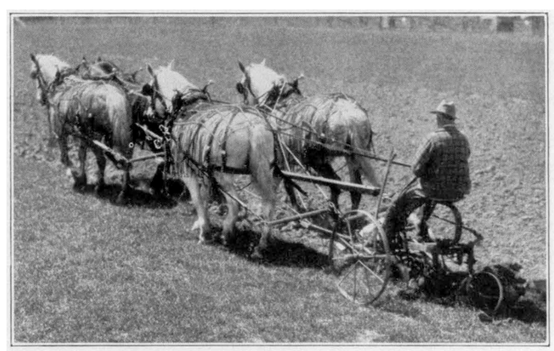

FIG. 2.—FOUR HORSES WITH A TALKINGTON HITCH ON A SULKY PLOW

> "The four-horse team and Talkington evener ... have the line of draft about right for a single sulky plow or a two-bottom gang. The horses are spread well apart, wagon double trees being used for the leaders. They have plenty of air and keep cooler than when crowded together. The team in Fig. 2 is pulling a 16-inch sulky plow in old alfalfa sod. Such an outfit is very good also for plowing under sweet clover in the spring." - M. L. Wilson, *Big Teams in Montana*, 1925.

23.3 Drawbar and Pulley Horsepower

For traction engines, tractors, and locomotives, the most important measure of performance is often not the power developed inside the cylinders, but the power available to perform useful work.

When pulling a load, the useful power is delivered through the drawbar and is known as **drawbar horsepower (DBHP)**.

Drawbar horsepower is determined by measuring two quantities:

- The pulling force at the drawbar.
- The speed at which the load is moved.

Power is simply the product of force and velocity.

For measurements expressed in pounds force and miles per hour:

$$hp_d = \frac{Fv}{375}$$

where

- F = drawbar pull (lb)
- v = speed (mph)

The constant 375 is derived from Watt's definition of horsepower:

$$375 = \frac{33000 \cdot 60}{5280}$$

23.3.1 Example

A tractor produces a drawbar pull of 2,025 pounds while travelling at 5 miles per hour.

The drawbar horsepower is:

$$hp_d = \frac{2025 \cdot 5}{375} = 27hp$$

23.3.2 Measurement

Historically, drawbar horsepower was determined by pulling a known load while measuring both force and speed.

A simple modern method uses a hydraulic cylinder placed between the vehicle and the load. The hydraulic pressure within the cylinder is proportional to the pulling force. By measuring pressure and vehicle speed, drawbar horsepower can be calculated directly.

Traction engines often performed a second role as stationary power plants. When operating a threshing machine, sawmill, elevator, or water pump, power was delivered through the belt pulley. This useful output is known as **pulley horsepower**.

Because power is lost in gears, bearings, wheels, wheel slip, and rolling resistance, drawbar horsepower is always less than the power available at the engine shaft. As a result, the same machine may have different ratings for pulley horsepower and drawbar horsepower depending on how the power is used.

23.4 Marketing Power Designations

The transition from animal power to mechanical power created an immediate need for simple and easily understood power ratings.

Farmers were accustomed to judging machinery by the number of horses required to perform a task. Steam-engine manufacturers therefore adopted horsepower ratings that allowed prospective customers to compare a machine's performance with that of horse-drawn equipment.

Unfortunately, horsepower could be measured in several different ways. As a result, the horsepower advertised by a manufacturer was not always the same quantity that an engineer would measure in a test.

Traction engines commonly carried two power ratings. Examples include:

- Case 18–50
- Case 22–65
- Case 28–80

The first number represented **boiler horsepower**, a measure of the boiler's steam-generating capacity. The second number represented **belt (pulley) horsepower**, the useful power available for driving stationary machinery.

Early gasoline tractors adopted a different convention. Machines were often advertised using **drawbar horsepower** and **belt horsepower**.

For example:

- Case 20–40

indicated approximately 20 drawbar horsepower and 40 belt horsepower.

These ratings reflected the two principal jobs expected of a farm power unit: pulling implements in the field and operating stationary machinery through a belt pulley.

Horsepower ratings found in advertisements, sales literature, and even on engine nameplates should therefore be interpreted carefully. Depending on the manufacturer and the period, the numbers may refer to boiler horsepower, indicated horsepower, brake horsepower, pulley horsepower, or drawbar horsepower.

23.5 Measuring Torque

As steam engines and gasoline tractors became common, manufacturers naturally wished to advertise the capabilities of their machines. Farmers, however, wanted more than claims and sales literature. They wanted objective measurements that allowed one machine to be compared fairly against another.

One response was the Winnipeg Tractor Trials, held between 1908 and 1913. The event was originally conceived as an industrial exhibition. At the time, Winnipeg was the principal railhead serving the recently settled prairie provinces of Saskatchewan and Alberta, and manufacturers were eager to demonstrate their machinery to western farmers.

The character of the event changed when agricultural researchers became involved. Professors from the Manitoba Agricultural College, later incorporated into the University of Manitoba, introduced scientific testing methods and standardized measurements. What began as a machinery exhibition evolved into a controlled engineering experiment in which competing tractors and engines could be compared under identical conditions.

The Winnipeg Trials became a forerunner of the better-known Nebraska Tractor Tests established after the First World War. Manufacturers quickly realized that independently verified performance figures carried far more weight than advertising claims alone.

To compare machines fairly, the judges needed a way to measure the power delivered at the engine shaft. This required the measurement of **torque**.

23.5.1 Gaspard de Prony

The solution had been developed nearly a century earlier by the French engineer Gaspard Clair François Marie Riche de Prony.

In 1826, de Prony described a simple device capable of measuring the torque produced by a rotating shaft. The device became known as the **de Prony brake** and remained one of the most widely used methods of determining engine power throughout the nineteenth and early twentieth centuries.

23.5.2 The De Prony Brake

The de Prony brake consists of a friction brake wrapped around a rotating drum or flywheel. Friction between the brake and the rotating surface attempts to carry the brake assembly around with the shaft.

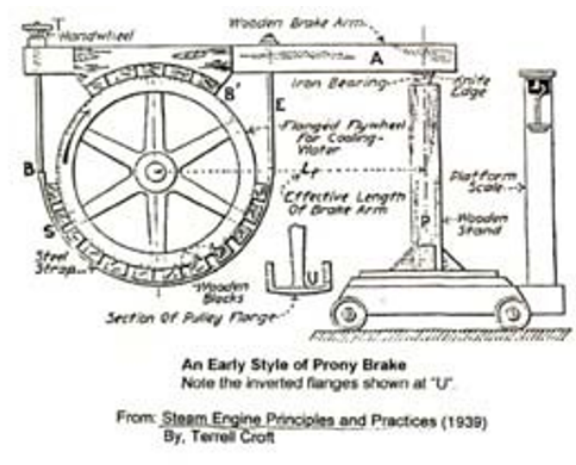

Fig. 1 De Prony Brake

A lever arm attached to the brake resists this motion. The force acting at the end of the lever can be measured using a scale or other force-measuring device.

The arrangement converts the engine's torque into two directly measurable quantities:

- Force
- Distance

Since torque is simply force multiplied by distance,

$$T = F \cdot L$$

where:

- T = torque
- F = measured force

- L = length of the brake arm

Once torque is known, the engine power can be determined if the rotational speed is also known.

Each revolution causes the measured force to travel a distance equal to the circumference of a circle having radius L. Therefore the distance travelled in one revolution is:

$2 \cdot \pi L$

If the shaft rotates at r revolutions per minute, the work performed each minute is:

unexpected symbol F

Dividing by Watt's definition of horsepower gives:

unexpected symbol F

where:

- L = brake-arm length (ft)
- r = rotational speed (rpm)
- F = measured force (lb)

This remarkably simple equation allowed engineers to determine brake horsepower using only a scale, a lever arm, and a tachometer.

23.5.3 A Convenient Shortcut

Practical engineers are rarely content with complicated arithmetic.

If the brake-arm length is chosen so that:

$2 \cdot \pi L$

is a convenient multiple of 33,000, the horsepower equation simplifies considerably.

A commonly used arm length of approximately 63 inches (5.25 ft) produces the convenient relationship:

$hp = \frac{r \cdot F}{1000}$

At 250 rpm, each 4 pounds indicated on the scale corresponds to approximately 1 horsepower.

This simple rule allowed engineers and test officials to determine engine power quickly without extensive calculation, making the de Prony brake particularly useful at field tests such as the Winnipeg Tractor Trials.

The de Prony brake transformed horsepower from a manufacturer's claim into a measurable quantity. For perhaps the first time, competing machines could be compared using objective engineering data rather than reputation or advertising.

23.5.4 Horsepower and Torque

Torque and horsepower are related, but they are not the same thing.

Torque is a twisting force. If a wrench is placed on a bolt and a force is applied at the end of the wrench, a torque is produced.

Horsepower is the rate at which work is performed.

A steam engine may produce a large torque while turning slowly. Another engine may produce a smaller torque but turn much faster. Both may produce the same horsepower.

A useful analogy is a water wheel.

- Torque answers the question: "How hard is it pushing?"
- Horsepower answers the question: "How fast is work being done?"

An engine producing torque but not rotating is doing no work. Since power is the rate of doing work, the horsepower at zero speed is zero regardless of the torque being produced.

23.5.5 A Practical Note on de Prony Brakes

Textbook descriptions of a de Prony brake often show a simple friction band wrapped around a rotating drum. In practice, large horsepower measurements generate enormous quantities of heat and require both lubrication and cooling.

Historically, beef tallow was commonly used as a lubricant for the brake band. The tallow reduced wear, prevented chatter, and helped provide a reasonably consistent coefficient of friction during testing.

Many modern Prony brakes use a hollow brake wheel resembling a steel tire. Cooling water is continuously introduced into the wheel while the brake is operating. Centrifugal force distributes the water around the inside of the rotating wheel, where it absorbs heat generated by friction.

An internal pickup located near the outer circumference collects the water and carries it away for disposal. This simple arrangement allows substantial amounts of power to be absorbed continuously without overheating the brake.

These practical details remind us that a Prony brake is actually a power-absorbing device. A 100-horsepower engine delivers approximately 255,000 BTU per hour to the brake, nearly all of which must ultimately be removed as heat.

23.6 Indicated Horsepower

The de Prony brake determines power by measuring torque at the engine shaft. A steam engineer, however, has another option.

Because the pressure within the cylinder can be measured using a steam indicator, it is possible to estimate the power produced directly by the piston. This measurement is known as **indicated horsepower (IHP)**.

The indicator diagram introduced in the previous chapter provides the information needed to estimate the average pressure acting on the piston throughout its stroke.

Once the average pressure is known, the force acting on the piston can be calculated from:

Force = Pressure × Area

The work performed during one stroke is then:

Work = Force × Distance

Multiplying by the number of strokes per minute gives the horsepower produced within the cylinder.

23.6.1 Boiler Pressure vs. Cylinder Pressure

A boiler pressure gauge measures the pressure available within the boiler. This is not necessarily the same pressure acting on the piston.

Before reaching the cylinder, steam must pass through the dry pipe, throttle, governor, steam chest, valve passages, and finally the admission port. Each restriction causes a pressure drop. Steam engineers refer to these losses collectively as **wire drawing**.

As a result, the pressure available to perform work within the cylinder is generally lower than the pressure indicated by the boiler gauge.

The indicator card records the pressure actually acting on the piston and is therefore a more useful tool for determining engine power. In the following example, the pressure term represents the effective cylinder pressure rather than the boiler pressure.

The boiler gauge tells the engineer what pressure is available.

The indicator card tells the engineer what pressure the piston actually receives.

23.6.2 A Simple Approximation

A complete analysis would require determining the exact area enclosed by the indicator diagram. In practice, a useful estimate can often be obtained by replacing the curved expansion line with simple geometric shapes and applying the familiar **PLAN** formula:

$HP = \frac{PLAN}{33000}$

where:

- P = Effective cylinder pressure (psi)
- L = stroke length (ft)
- A = piston area (in²)
- N = power strokes per minute

Consider an engine modeled on the Case 22-65 operating with:

- Cylinder pressure: 100 psi
- Cutoff: 33% of the stroke
- Stroke: 11 in
- Bore: 10 in
- Speed: 225 rpm

Assume that full cylinder pressure acts during the first one-third of the stroke and then falls linearly to zero during the remaining two-thirds.

The entire calculation can then be written as:

$$\begin{aligned} HP &= \frac{P \cdot L \cdot A \cdot N}{33000} \text{ where } \begin{cases} P \to \frac{1}{3} P_c + \frac{2}{3} \frac{P_c}{2} \\ L \to \frac{S}{12} \\ A \to \pi \left(\frac{B}{2}\right)^2 \\ N \to rpm \end{cases} \text{ where } \begin{cases} P_c \to 100 \\ S \to 11 \\ B \to 10 \\ rpm \to 2 \cdot 225 \end{cases} \\ &= 65.450 \end{aligned}$$

The individual terms are easy to identify.

23.6.2.1 Pressure

The mean effective pressure is approximated by a rectangle plus a triangle on the indicator card:

$$P = \frac{1}{3}P_c + \frac{2}{3}\left(\frac{P_c}{2}\right)$$

Substituting:

$$P = \frac{1}{3}(100) + \frac{2}{3}(50)$$

$$P \approx 67psi$$

Notice that this simplifies to:

$$P = \frac{2}{3}P_c$$

for the assumed cutoff and linear expansion.

23.6.2.2 Length

The 11-inch stroke becomes:

$$L = \frac{11}{12} = 0.917ft$$

23.6.2.3 Area

For a 10-inch bore:

$$A = \frac{\pi \cdot 10^2}{4}$$

$$A = 78.500in^2$$

23.6.2.4 Number of Power Strokes

A double-acting engine produces two power strokes per revolution:

$$N = 2rpm$$

$$N = 2(225) = 450\frac{strokes}{min}$$

23.6.2.5 Applying PLAN

Substituting these values into:

$$HP = \frac{PLAN}{33000}$$

gives:

$$HP = \frac{67 \cdot 0.917 \cdot 78.500 \cdot 450}{33000}$$

$$HP \approx 65.500hp$$

23.6.3 Discussion

Using only a simple approximation of the indicator diagram, the estimated output is approximately 65 horsepower, remarkably close to the rated output of a Case 22-65.

The result illustrates the power of the indicator diagram. By estimating the mean effective pressure and applying the PLAN formula, a steam engineer can obtain a surprisingly accurate estimate of engine output using only a few dimensions and some straightforward arithmetic.

23.7 Summary

The various methods of measuring power discussed in this chapter approach the same question from different directions.

- Drawbar horsepower measures power delivered to the load.
- Brake horsepower measures power delivered at the shaft.
- Indicated horsepower measures power produced within the cylinder.

Each method tells part of the story.

Perhaps the most remarkable result is that a simple indicator diagram and a few engine dimensions allow the steam engineer to estimate engine power with surprising accuracy. Long before electronic sensors and computerized data acquisition, steam engineers were able to analyze engine performance using little more than pressure measurements, geometry, and arithmetic.