POWER MEASUREMENT

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INTRODUCTION

Power is defined as the rate of doing *work* and is measured in English customary units of ft.lbs./min. *Work* is considered to be a force acting through a distance and is measured in ft.lbs. For example if a force is used to move a 10 lb. load (mass) through a distance of 100 ft., 1000 ft.lbs. of work has been accomplished. In this example, 1000 ft.lbs. of work can be accomplished by moving a 100 lb. load 10 ft. or any combination of distance and load that has a product of 1000 ft.lbs. The time, seconds or minutes, expended when a force moves a load through a given distance is considered when determining power. Work is accomplished only if the mass is moved. *Energy*, the capacity for doing work, has the same units of measure as work (1).

Torque is a load applied to a lever arm to produce or tend to produce rotary force. Torque is similar to work in that its English customary units of measure is foot pounds. Torque is sometimes defined simply as a turning effort (2). Application of torque does not ensure moving the lever arm. For example if a 100 lb. load is applied to a 1 ft. lever arm, 100 lb.ft. of torque is produced regardless of any rotation. It will produce rotation only if it is not balanced by an equivalent torque (3). To differentiate *torque* from *work* some texts, reverse the units using lb.ft. for torque and ft.lbs. for work. If torque produces rotation, *work* is accomplished. Torque is an important concept when defining and measuring rotary power.

HISTORY OF POWER MEASUREMENT

The problem of defining power came about when engines, especially steam engines, were introduced. James Watt developed one of the first successful steam engines in England in the latter part of the 18th century. Since most of the power at that time was produced by men and horses, he decided to compare the power of his steam engines to that of horses. He conducted a series of tests with draft horses and determined the average amount of work, a draft horse could do in a certain length of time (4). Watt observed that a horse could lift 366 lbs. of coal from a mineshaft at the rate of 1 ft./s or 60 ft./min. In other words, the work accomplished was equal to 21,960 ft.lbs. (366 lbs. × 60 ft.). He rounded the 21,960 to 22,000 and increased this value by 50%, (11,000 lb.ft) to 33,000 ft.lbs/min, deliberately underrating his steam engines. One *horsepower* (Hp) is defined as 33,000 ft.lbs./min. or 550 ft.lbs./s. This basic unit is still used today; but because Hp was developed in England using English customary units, the term *Power* a non-unit-specific term has replaced it. The SI unit of power is named W (watt) for James Watt.

POWER MEASUREMENT – SI UNITS

Work as explained in the introduction is a force acting through a distance. *Force* in SI units is measured in *N* (newtons) named after scientist Sir Isaac Newton. A *newton* is the unit of force required to accelerate one kg of mass one meter per second per second. The derived unit for *work* in SI units is the $N \cdot m$ (newton meter), and this combination has been given the name J(joule). Since one J is so small the kJ (kilojoule) or MJ (megajoule) is often used as measures of *work* or *energy* (1,3). To convert ft.lbs. to J multiply by 1.355818 (5).

Power is identified as *W* to honor James Watt and is equal to a newton meter per second (N m /s). One customary Hp is the equivalent of 745.7 W and one kW (kilowatt) is the equivalent of 1.341 Hp (3).

Applications that involve fluid power, hydraulic power, heat exchange capacity, water power, and electrical power are also measured. These applications may use the customary power measurement units Hp, Btu/min, or Btu/h. They may also be measured in SI units, J/s, W or kW. Electrical power is measured in W or kW (5). This article will focus on mechanical power, rotary and linear measurements.

POWER MEASUREMENT TERMS

It is important to understand that the amount of power varies depending on how and where it is measured (6). To clearly understand power measurement, additional terms must be defined.

Dynamometer – An instrument used to measure linear or rotary power. Both types determine power by measuring force, time and the distance through which the force is moved. Rotary dynamometers may be classified as brake or torsion. Linear dynamometers are called drawbar (Db) dynamometers .

Linear – Db dynamometers measures pull, and the velocity of the vehicle making the pull.

Rotary dynamometers measure power at the flywheel, power take off (PTO) shaft or drive wheel. Dynamometers may employ electric generators or eddy currents, air, water or hydraulics to apply the load. All rotary absorption type dynamometers generate heat when the load is applied and this heat may be dissipated by circulating water through the dynamometer (7).

Brake Power – Power output of the crankshaft and measured at the flywheel. Brake Power is also called flywheel or engine power. (The term brake power came about because the first devices for measuring power were Prony Brakes.) Brake power may be measured with the engine stripped of accessories such as alternator, fan, water pump, exhaust system, air conditioner, hydraulic and pneumatic systems. Engines are tested on stands in the laboratory with systems needed by the engine to start and run provided.

Maximum Brake Power – the maximum power an engine will develop with the throttle fully open at a specific speed. Automobile engines are usually rated with throttles fully open at the speed (rpm) their power curve peaks. Automobile engines can maintain maximum power for only a short duration. Tractor engines are designed with governors to maintain consistent operating speeds in a range that will allow the engine to be operated at demand loads over extended time periods.

Observed Power – Power without any correction for atmospheric temperature pressure (barometric) and vapor pressure.

Corrected Power – Power has been adjusted (corrected) for atmospheric conditions. Engines perform better at cooler temperatures and higher barometric pressures because more oxygen can enter the combustion chamber and more fuel can be burned.

Hydraulic Power – Power developed by a hydraulic pump. Pump power is calculated using flow rate and pressure.

Torque Reserve – Also known as Torque Rise is the additional torque that is available beyond torque at maximum power. Torque reserve is very important in tractors in that it provides what is called lugging ability so the tractor can continue through high pulls or loads without killing the engine. It is not uncommon for tractor engines today to exhibit a 30 to 40% torque rise.

Indicated Power – Power generated in the engine on top of the pistons. It takes into account mean effective pressure on each cylinder, length of stroke, area on top of piston and speed.

Friction Power – The Power required to run the engine at any given speed without production of useful work. Friction power of an engine can be found by subtracting brake power from indicated power.

Fuel Equivalent Power – Computed from the product of consumption rate and heating value of the fuel.

There are many other power terms used in advertising and service literature. For example, *advertised*, *certified*, *effective*, *guaranteed*, *net engine* and *rated*, to name a few. These terms can be confusing and are sometimes used in place of terms above. Because of this, they should be used judiciously and only if they are defined.

If the objective of measuring power is to determine internal combustion engine power efficiencies then *fuel equivalent power*, *indicated power*, *friction power* and *brake power,* all examples of engine power can be measured or calculated. These powers in turn can be used to ascertain engine power efficiencies such as *indicated thermal efficiency*, *brake thermal efficiency* and *mechanical efficiency* (8). It is beyond the scope of this article to describe these and other engine power efficiency terms.

Transmitted Power – Engine Power transmitted from flywheel to a point on a machine or vehicle. Axle, PTO, Drawbar and Chassis are examples of transmitted power. Transmitted power may also be called *Output Power*. Transmitted powers will always be less than flywheel power because of the losses in the drive train. Of the transmitted powers identified above, axle, wheel, PTO and Drawbar, drawbar power will be the lowest and most variable because of losses due to the power train, tractive elements of the vehicle and the surface it is operating on. PTO power is approximately 96 % of flywheel power and Db power is approximately 86% of PTO power (9). *ASAE D497.4 Agricultural Machinery Management Data* gives more specific ratios that take into account, tractor type, 2WD, MFWD, 4WD, Track (belted) and tractive conditions, concrete, or firm, tilled and soft soils (10).

MEASURING LINEAR AND ROTARY POWER

Mechanical Power may be *linear* or *rotary*. *Linear* power occurs when a force is exerted with a linear velocity. A tractor pulling a plow (power transmitted to the drawbar) is an example of linear power and in English units is usually defined as DbHp (drawbar horsepower) in that the force or load component of power is measured at the tractor's drawbar with a pull meter in pounds. Power transmitted to the PTO (Power Take Off) shaft is rotary power and is called PTO power. Older tractors produced a similar rotary power called *belt* (brake) horsepower. On these older tractors the power was measured from the belt pulley because they were not equipped with a PTO shaft. Today's larger tractors may not be equipped with PTO shafts because they are used for pulling large loads such as primary tillage tools. Their power is measured at the engine flywheel and is published as flywheel power. Chassis dynamometers also measure rotary power and are most commonly used for measuring truck or automobile power at the drive wheels.

Linear Power

The following formula is convenient for measuring linear power using either SI or English units DbHp(11,12). Because W is so small (745.7 W/Hp,) kW is normally used to identify power in SI units. The constants shown in formulas below assume these units.

DbP = drawbar power expressed in kW [Hp]

DbP = F×S/K

F = force measured in kN [lb]

S = forward speed, km/hr [mph]

K = units constant, 3.6 [375]

Example problem:

A tractor is pulling a tillage tool that exhibits 53.3*kN* [12000 *lb*] load at 8.05 *km/hr* [5 mph] speed.

Solving problem using SI units:

$$119.3kW = \frac{53.38kN \times 8.05km/hr}{3.6}$$

Working the same problem using customary English units:

$$160\ DbHp = \frac{12000lb.(Pull) \times 5mph}{375}$$

Solving problem in customary units using unit factoring without the 375 conversion factor.

$$160 \text{ DbHp} = \frac{12000 lb.}{Pull} \times \frac{5 miles}{hr.} \times \frac{hr.}{60 min.} \times \frac{5280 ft.}{mile} \times \frac{Hp.}{33000 ft.lb./min.}$$

Rotary Power

Rotary power, is the product of work/rev and rotary speed . Torque, an important concept when measuring rotary power, is the product of lever arm length and a force acting perpendicular to it. Rotary power may be measured with a Prony brake, a simple form of an absorption dynamometer. A Prony brake consists of an adjustable brake band or friction device that contacts a rotating member of the engine usually the flywheel. The lever arm is part of the friction device. As the adjustable friction device is tightened the load on the engine is increased. This load is sensed by a scale or load cell attached to the lever arm preventing it from rotating with the flywheel. A tachometer measures the rotary speed of the flywheel in rpm.

To measure brake or rotary power the following information is needed.

Rotary speed of the flywheel or rotating member. Rotary speed is the amount of angular rotation per unit of time. The most common unit for rotary speed is revolutions per minute – rpm.

Length of lever arm

Load on lever arm

Example Problem to find the brake power (BP) in SI units (kW) and English customary units (Hp) of a small engine with a Prony brake attached.

Given:

Rotary Speed - Engine is turning 3000 rpm after the brake band has been adjusted to obtain force on lever arm.

Length of Level Arm - Lever arm is 0.3048 meter [1 ft] long.

Load - Force (load) 44.48222 N [10 lbs] is measured by scale attached to end of lever arm.

A convenient formula to find the BP of small engine identified above using SI or English units.

BP = brake power expressed in kW[BHp]

BP = 2 $\pi \times$ T $\times$ N/K

T = engine torque $N \cdot m$ [lb-ft]

N = number of revolutions per minute, rpm

K = units constant = 60,000 [33,000]

Solving problem in SI units:

$$4.26kW = \frac{(2\times3.14)\times44.48222N\times0.3048m\times3000rpm}{60000}$$

Solving problem using English units.

$$5.71BHp = \frac{(2\times 3.14)\times 10lb \times 3000rpm}{33000}$$

TRACTOR TEST CODES- STANDARDS

Procedures and codes for testing the power and performance of tractors have been developed by a number of organizations including the Society of Automotive Engineers (SAE), The Society for Engineering in Agricultural, Food, and Biological Systems (ASAE), Nebraska Tractor Test Center (NTTC) and the Organization for Economic Cooperation and Development (OECD) (12,13,14). All of these organizations test both linear and rotary power of tractors and their codes identify standards for PTO (rotary), and drawbar (linear) power in addition to three - point hydraulic lift capacities and sound level measurements. They also record in addition to the environmental conditions, fuel type, fuel temperature, fuel and lubricants used and consumed and other variables that impact the performance of the tractor. When measuring Db power, all factors considered in the PTO tests are accounted for plus those that impact traction which include, gear, tractor ballast, tires and surface. Drawbar performance is measured on a concrete track for consistency.

Because tractor drawbar performances are determined on concrete, Frank Zoz, retired John Deere Product Engineer has developed "*Predicting Field Performance*" an "Excel" template to predict tractive performance and efficiency of tractors on dirt using the primary inputs, PTO power, ground speed, ballast, tractor dimensions, implement hitch, tire size, and pressure configuration that are used in the SAE, NTTC & ASAE official tests. Tractor performance including pull, drive wheel slip, and forward speed are predicted on soils with different penetrometer readings. The spreadsheet predicts performance at given weights or can be used to calculate required tractor ballasting, front and rear. (15).

TRACTOR POWER EFFICIENCIES

Tractor power efficiencies consider drive train and traction elements. The efficiency of transmitting engine, PTO or axle (input) power to the tractor's drawbar (output) power may be identified as Power Delivery Efficiency (PDE), or Tractive Efficiency (TE). PDE is the ratio of Db to flywheel or Db/PTO. TE is the ratio of drawbar to axle power, Db/Ax (15,16). (Since PTO is approximately 96% of flywheel it can be used for flywheel in determining PDE). PDE is more meaningful than TE when comparing the power efficiencies of tractors because the entire drive train is taken into account. For example when comparing the power efficiency of a wheel tractor to a belted (track) tractor, the effects of the drive train, clutches, transmission, as well as the tractive elements are included in PDE but not TE.

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