

SYSTEM AND METHOD TO USE PROPELLERS AND ELECTRIC MOTORS TO MEASURE THE POWER PRODUCED BY INTERNAL COMBUSTION ENGINES

5 FIELD OF INVENTION

Embodiments of the present invention provide systems and methods using propellers and electric motors to measure the power and efficiency of internal combustion engines.

10

BACKGROUND

Model airplane internal combustion engines are advantageous for use as powerplants in Unmanned Aerial Vehicles (UAVs) due to their easy off-the-shelf availability and low cost. Certain engineering tasks in the development of UAVs, based on specific performance and operational requirements, may require knowledge of the power and efficiency characteristics of the engine as a function of the shaft revolutions per minute (rpm) and throttle setting. For example, when selecting or designing a propeller for a Vertical Take Off and Landing (VTOL) UAV, one may wish to check that the power required by the aerodynamic design of the propeller is within the shaft power available from the engine. Other examples are the selection of an engine operating point for optimal endurance of the UAV, and/or the development of computer models of the engine for flight simulators.

Unfortunately, performance characteristic information for the engines is not available in the engine literature (e.g. operating manuals, brochures, specifications from the supplier etc.). Specifications of available engine power, if any, are limited to only the maximum power produced by the engine. The reliability of this value is questionable, as it may assume a certain configuration for the propulsion system (e.g. type of exhaust pipe, fuel mixture composition, etc.), which may not be suitable or optimal for the UAV being developed. Hence the power and efficiency characteristics of the engine need to be obtained by measurement.

Current techniques for measuring engine power involve using instruments such as dynamometers and load cells. These techniques involve placing the instrument for measuring power on the same test stand as the engine. But these engines, especially small single-cylinder types, produce vibrations that may damage the test instruments or, at best, cause inaccuracies in the measurements.

It would therefore be a great improvement in the art if a system and method could be developed to overcome one or more of the deficiencies cited above.

SUMMARY

One aspect of the present invention provides a method for determining a power produced by a internal combustion engine for use in selecting a propeller for the engine, the method comprising the steps of: determining power versus motor shaft speed characteristics for at least one propeller coupled to the motor shaft of and driven by an electric motor having a similar power rating and motor speed range as that of the internal combustion engine; connecting said propeller to an engine shaft of said internal combustion engine; measuring a speed of said engine shaft at a given throttle setting while said propeller is connected to said internal combustion engine; and using said speed measurement and said power versus motor shaft speed characteristic of said motor to determine the power produced by said engine.

In some embodiments, the step of determining the power versus motor shaft speed characteristics may further include the steps of: connecting said propeller to said motor shaft of said electric motor; and measuring the power required to produce a given motor shaft speed for a plurality of motor shaft speeds. In alternate embodiments, the method may further include determining the power produced by the engine for a plurality of engine shaft speeds.

In further embodiments, the method may further include measuring a fuel flow rate for said engine for each of a plurality of propellers at a plurality of engine throttle settings. The step of measuring the fuel flow rate may further include: measuring an initial mass of a fuel tank supplying fuel to said engine at a first time; measuring the

mass of said fuel tank again after a period of time; calculating a change in mass of said fuel tank; and dividing said change in mass by said period of time to determine said fuel flow rate.

- 5 The fuel flow rate at the given throttle setting, and the engine power, may be used to calculate an efficiency for the engine. The engine efficiency may be calculated using the formula $\eta \equiv \frac{P}{\dot{m}_f Q}$, wherein η is said engine efficiency, P is said power produced by said engine, $\dot{m}_f$ is said fuel flow rate, and Q is a constant depending on a type of fuel being used.

10

In further embodiments, the method may further include: calculating an efficiency curve for a plurality of propellers at a plurality of engine shaft speeds and engine throttle settings; and selecting one of said plurality of propellers to meet a desired criteria. The desired criteria may be one of a desired engine efficiency or a desired engine power. A tachometer may be used to measure the speed of the propeller when connected to the engine shaft.

15

BRIEF DESCRIPTION OF THE DRAWINGS

- 20 Embodiments of the invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

Figure 1 is a block diagram illustrating one embodiment of an apparatus for measuring the power and motor shaft speed generated by an electric motor with an attached propeller according to the present invention;

25

Figure 2 is a graph illustrating the power versus motor shaft speed characteristics for the apparatus of Figure 1 using a number of different propellers;

30

Figure 3 is a block diagram illustrating one embodiment of a system for measuring the engine shaft rotational speed and fuel flow rate of an internal combustion engine driving the propeller used in the system of Figures 1 and 2;

5 Figure 4a is a graph showing engine power versus engine shaft rotational speed obtained using a plurality of propellers at a single engine throttle setting using the systems of Figures 1 and 3;

10 Figure 4b is a graph showing engine efficiency versus engine shaft rotational speed obtained using the same plurality of propellers at the same engine throttle setting as Figure 4a using the systems of Figures 1 and 3;

15 Figure 4c is a graph showing engine power versus engine shaft rotational speed curves for a plurality of engine throttle settings obtained by repeating, at the plurality of throttle settings, the procedure used to obtain Figure 4a;

20 Figure 4d is a graph showing engine efficiency versus engine shaft rotational speed for the same throttle settings as shown in Figure 4c, obtained by repeating the procedure used to obtain Figure 4b; and

Figure 5 is a flow chart illustrating one embodiment of a method to use the power versus propeller speed characteristics for the electric motor to determine the amount of power produced by the internal combustion engine.

25 DETAILED DESCRIPTION

30 Embodiments of the present invention provide a system and method to use propellers and electric motors to determine the power of a corresponding internal combustion engine having similar power characteristics and speed ranges as the electric motor. The embodiments provide a technique whereby the instruments and methods for measuring the power and speed of the propeller connected to the electric motor or internal combustion engine are separated from the engine test apparatus, and

are thus not subjected to the high-vibration operating environment caused by the engine. This is an improvement over prior art systems. The power of the engine may then be determined with reference to the corresponding power characteristics obtained from the measurements of the electric motor. In some embodiments, fuel flow rates at various
5 throttle settings are also calculated for the internal combustion engine. These fuel flow rates may then be used with the power characteristics to determine an efficiency of the internal combustion engine. In additional embodiments, multiple propellers may be used. This will be discussed in more detail below with reference to Figures 1-5.

10 Figure 1 is a block diagram illustrating one embodiment of an apparatus 100 for measuring the power of an electric motor 102. The electric motor 102 drives a drive shaft/motor shaft 106 that is coupled to a propeller 104. In this embodiment, the propeller 104 includes two blades, 104a, 104b. A power and speed (measured in rotations per minute (rpm)) transducer 108 is coupled to the drive shaft 106. The
15 transducer 108 provides a measurement of both the power produced by the engine 102, and the rotating speed of the drive shaft 106. Using the transducer 108, the rotating speed of the drive shaft 106 may be measured directly. Alternately, the rotating speed of the drive shaft 106 may be measured by measuring the speed of the propeller 104 connected to the drive shaft 106. As the electric motor 102 has
20 much lower vibrations than the internal combustion engine, vibration-induced damages and measurement inaccuracies of the transducer 108 are avoided. While the speed of the drive shaft 106 is measured in rpm, it is understood that other speed measurements may also be used.

25 The propeller 104 may be an off-the-shelf propeller having a blade diameter and pitch which are typically used with the internal combustion engine. The propeller 104 may be selected using the engine specifications, which typically recommend a number of off-the-shelf model airplane propellers for use with the engine. For example, specifications for a 20cc engine may recommend 17x10, 18x6 and 18x8 off-the-shelf two-bladed propellers.
30 Any one of the recommended propellers, or other types of propellers, may be used with the embodiments of the present invention.

One example of the transducer 108 is the Datum Electronics M420 Series of torque transducers. It is understood that other types of transducers may also be used.

By measuring the power produced by the motor 102 to drive the load provided by the propeller 104 at a particular drive shaft speed, for a range of drive shaft speeds and motor power, the power versus motor shaft rotational speed characteristics of the motor 102 driving a particular propeller load may be plotted graphically (see Figure 2). In some embodiments, a range of drive shaft speeds may be obtained by varying the speed controller of the electric motor 102.

The propeller 104 may be successively replaced by other off-the-shelf model airplane propellers. The measurement of power for a range of motor shaft rotational speeds, and the plotting of the power versus motor shaft rotational speed characteristic curve, may then be repeated for each of these off-the-shelf propellers. As previously discussed, the propellers 104 may have diameters and pitches in the region of that typically used for the internal combustion engine 202 (Figure 3). For example, if an off-the-shelf two-bladed 18x8 propeller was initially used as propeller 104, other off-the-shelf two-bladed propellers with diameters ranging from 16 to 20 inches and pitches ranging from 6 to 12 inches may be successively tested. The use of a wider range of diameters and pitches will result in a wider range of measured power and motor shaft rotational speed characteristics. By way of example and not limitation, the propellers 104 may also have three or more blades, each having different lengths and different blade pitch characteristics.

Figure 2 shows a graph, designated generally as reference numeral 120, illustrating the power versus motor shaft rotational speed characteristic curves for the electric motor 102 of Figure 1 using a variety of different off-the-shelf propellers. For the purposes of illustration, the measured power (watts) is shown on the Y-axis 122, while the measured motor shaft rotational speed (rpm) is shown on the X-axis 124. A power versus motor shaft rotational speed curve 126 may then be plotted, based on the measurements obtained from the apparatus 100. As discussed above, additional power versus motor shaft rotational speed curves 128, 130, etc. may be plotted for a variety of off-the-shelf propellers. These curves may then be used in a method for determining the power produced by an internal combustion engine according to one embodiment of the present invention. This will be discussed in more detail below with respect to Figures 3-5.

The power and speed range required for the electric motor 102 will depend on the type of internal combustion engine that one wishes to use. For example, a 20cc internal combustion engine may have maximum power somewhere in the range or
5 1500-2000 Watts, and a maximum speed somewhere in the range of 8-10,000 rpm. It is understood that, as long as the electric motor 102 is chosen to have a similar power and motor speed range as the desired internal combustion engine, various ranges for the power and engine speed may be used. The electric motor 102 may thus be selected such that the current and voltage required to operate in its normal
10 operating range is sufficient to meet the power and speed range for the engines being tested.

Figure 3 is a block diagram illustrating one embodiment of a system, designated generally as reference numeral 200, for measuring the engine shaft speed and,
15 optionally, the fuel flow rate of an internal combustion engine 202 at a given throttle setting. The propeller 104 previously discussed in Figure 1 is used again in the system 200 to determine the engine power, engine shaft rotational speed, and optionally the efficiency of the internal combustion engine 202 at the given throttle setting. The propeller 104 shown in Figure 3 is connected to a shaft 204 that is
20 driven by the internal combustion engine 202.

A measuring instrument 210 may be used to measure the speed (rpm) of the propeller 104 and/or the shaft 204 at a given throttle setting. In some embodiments, the measuring instrument 210 may be a hand-held tachometer. Other types of
25 measuring instruments may also be used. By using a measuring instrument that is not physically connected to the engine, the problems associated with damage to the measuring instrument and inaccuracies in the measurements, as discussed in the background section, may be eliminated, since the hand-held device 210 is not subjected to the vibrations of the engine 202. The measured engine shaft rotational
30 speed is used in conjunction with the power versus motor shaft rotational speed characteristic for the propeller 104 (previously plotted in Figure 2) to determine the power of the internal combustion engine 202 when driving the propeller 104 at any given throttle setting.

In some embodiments of the present invention, the test system 200 may also include a separate fuel tank 220 (Figure 3) that is placed on a weight scale 222. The tank 220 provides fuel to the engine 202 via a fuel line 224. The weight scale 222 measures the mass of fuel consumed by the engine at the measured engine speed and given throttle setting over a time period measured by a chronometer 226, such as, but not limited to a stopwatch. The instruments 222 and 226 are not physically connected to the engine 202, and are thus not at risk of damage or measurement inaccuracies caused by high engine vibrations. As discussed below with reference to Figures 4-5, this time measurement may be used to calculate the fuel flow rate for the engine 202 at the measured engine shaft speed and given throttle setting.

Figure 4a is a graph, designated generally with reference numeral 400, illustrating one example of a power versus engine shaft rotational speed curve for the engine 202. The graph 400 shows the engine power (watts) 402 on the Y-axis, and the engine shaft rotational speed (rpm) 404 on the X-axis. The power produced by the engine 202 at the measured speed and the given throttle setting may be recorded as a data point 406.

The mass and time measurements, together with the previously determined engine power, may be used to calculate the efficiency of the engine 202 at the measured engine shaft speed and given throttle setting. One method of determining the efficiency of the engine 202 may include using the weight scale 222 to measure the mass of the fuel tank 220 at a first time and again at a later time. The elapsed time may be measured using the chronometer 226. The fuel flow rate may then be calculated using Equation 1 below:

$$\dot{m}_f = \frac{\Delta m_{\text{tank}}}{\Delta t} \quad (1)$$

where $\dot{m}_f$ is the fuel flow rate calculated by dividing the change in mass of the fuel tank 220 Δm_{tank} , by the elapsed time Δt .

The efficiency of the engine 202 at the measured engine shaft speed and given throttle setting may be calculated using Equation 2 below:

$$\eta \equiv \frac{P}{\dot{m}_f Q} \quad (2)$$

5

where η represents the efficiency of the engine 202, P is the previously determined power produced by the engine 202, $\dot{m}_f$ is the fuel flow rate calculated using Equation 1 above, and Q is the heating value, or energy per unit mass of the fuel being used. For any given type of fuel, Q is a constant.

10

Figure 4b is a graph, designated generally with reference numeral 450, showing the engine efficiency (%) 452 on the Y-axis, and the engine shaft rotational speed (rpm) 454 on the X-axis. The efficiency produced by the engine 202 at the measured engine shaft rotational speed and the given throttle setting may be recorded as a data point 456.

15

The method, using one propeller at a given throttle setting to obtain the data points 406 in Figure 4a and 456 in Figure 4b, may be repeated at the same throttle setting using the plurality of off-the-shelf propellers 104, with the power versus motor shaft rotational speed characteristics shown in Figure 2, to obtain additional data points 408 and 410 in Figure 4a. Similarly, additional data points 458 and 460 may be generated for the efficiency curve reflected in Figure 4b. This results in the engine power versus engine shaft rotational speed characteristic curve 412, and engine efficiency versus engine shaft rotational speed characteristic curve 462 at the given throttle setting.

25

The method, using a plurality of propellers at a given throttle setting to obtain the engine power characteristic curve 412 in Figure 4a, and the engine efficiency characteristic curve 462 in Figure 4b, may be repeated at a plurality of throttle settings to obtain additional engine power versus engine shaft rotational speed characteristic curves 414 and 416 in Figure 4c, and additional engine efficiency

30

versus engine shaft rotational speed characteristic curves 464 and 466 in Figure 4d. This results in performance maps of engine power and efficiency.

It is understood that different curves could also be generated using the engine power and calculated efficiency as described above. For example, a power versus engine shaft rotational speed curve could be generated for each propeller at a plurality of throttle settings.

Figure 5 shows a flow chart illustrating one embodiment of a method, designated generally as reference numeral 500, to use the graph 120 to determine the amount of power produced by the internal combustion engine 202 based on the speed of the engine shaft 204. As discussed above, in some embodiments, the speed of the engine shaft 204 may be measured by measuring the corresponding speed of the propeller 104.

With reference to Figures 1 and 2, the method 500 includes a first step of determining power versus motor shaft speed characteristics for at least one propeller 104 driven by an electric motor 102 having a similar power rating and motor speed range as that of the internal combustion engine 202, as shown with reference numeral 502. The next step is to then connect the propeller 104 to the internal combustion engine 202, as shown with reference numeral 504. The next step is to measure the speed of the engine shaft 204 at a given throttle setting, as shown with reference numeral 506. This is accomplished by using the measuring instrument 210 to measure the speed of the propeller 104, as discussed above with reference to Figure 3. The final step in the method 500 is to use the engine shaft speed measurement and the power versus motor shaft speed characteristic of the motor 102 to determine the power produced by the engine 202 at the given throttle setting, as shown with reference numeral 508. This is discussed above with reference to Figures 2, 4a, and 4c. In some embodiments of the method 500, additional optional steps to determine, for example, the efficiency of the engine, may be included. This will be discussed in more detail below.

The first step 502 may be carried out as discussed above with reference to Figures 1 and 2. With reference to step 506, the speed of the engine shaft 204 connected to

the engine 202 may be determined by using the measuring instrument 210, such as a hand-held tachometer, to measure the rotational speed of the propeller 104. As the power required to produce a given engine/motor shaft speed for the propeller 104 was determined using the electric motor 102, this information may be extrapolated to the internal combustion engine 202 as well.

In some embodiments, the method 500 may optionally include using the calculated power of the engine 202 to select a propeller for the engine. The selection may be based, by way of example and not limitation, on a desired efficiency for engine 202 when driving the propeller at a given throttle setting. In alternate embodiments, the selection may be based on a desired engine power for a given throttle setting.

In these embodiments, the method 500 may further include calculating the power produced by the engine 202 for a plurality of propellers 104, at a plurality of engine shaft speeds and throttle settings, as shown with reference numeral 510.

As discussed above, in some embodiments of the present invention, in order to select a propeller for the engine 202, the method may include other steps as well. For example, an efficiency produced by the internal combustion engine 202 based on the engine shaft speed measured by the measuring instrument 210, and the fuel flow rate measured by the weight scale 222 and chronometer 226, may also be calculated. The fuel flow rate of the engine may be measured at the same time the engine shaft speed measurements are being made. Using the power produced by the engine from step 508, and the measured fuel flow rate, the efficiency of the engine 202 may be calculated, as discussed above with reference to Figures 4a-4d. Steps 504, 506 and 508 may be repeated using a plurality of propellers at the given throttle setting to obtain the engine power and efficiency characteristic curves for the given throttle setting as shown in Figures 4a and 4b respectively. Additional calculations may be done using the plurality of propellers at a plurality of throttle settings to obtain the engine power and efficiency characteristic curves for the plurality of throttle settings as shown in Figures 4c and 4d respectively, and as discussed with reference to step 510 above.

The method described above allows for the use of the characteristic curves that are generated to select or custom design a propeller for an internal combustion engine depending on a desired criteria. For example, the method allows for the selection of a propeller that provides a desired engine efficiency over a given power range. Similarly, the method allows for the selection of a propeller to have a desired power rating. The practical significance of engine efficiency in UAV applications is that, by selecting a flight operating point of the engine in the region of high efficiency, and designing a propeller to be aerodynamically efficient at that operating point and specified flight conditions, the endurance of the UAV can be potentially increased.

Embodiments of the method disclosed above provide several advantages over the prior art. As the technique involves using an electric motor of comparable power and motor shaft speed range to the engine, the capability to design an electric motor propulsion system to replace an existing internal-combustion engine system in a UAV is proven. The implication in the case of VTOL UAVs is the incorporation of perch-and-stare capabilities as, unlike internal-combustion engines, electric motors can be switched on and off remotely without the need for external starters.

As electric motors have much lower vibration levels than internal-combustion engines, there is little risk of damage to the power and rpm transducer. There is also little risk of vibration-induced inaccuracies in the measurements. The only measuring instrument used to record motor power is the power and rpm transducer. As there is no engine involved at this stage, the transducer is not subjected to the potentially damaging effects of high engine vibration.

Similarly, the measuring instruments used during operation of the internal combustion engine (hand-held tachometer, chronometer and weight balance) are not subjected to the potentially damaging effects of high engine vibration, as they are not physically connected to the engine. Using the apparatus 100 and system 200, and applying the method 500, power characteristics can now be measured without risk of damage to the measuring equipment, or measurement inaccuracies caused by high vibrations associated with the internal combustion engine. Simplicity is another feature of the technique, as it eliminates the need for special considerations (e.g. structural) related to engine vibrations in the design of test benches.

It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly
5 described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

CLAIMS

1. A method for determining a power produced by a internal combustion engine for use in selecting a propeller for the engine, the method comprising the steps of:
 - 5 determining power versus motor shaft speed characteristics for at least one propeller coupled to the motor shaft of and driven by an electric motor having a similar power rating and motor speed range as that of the internal combustion engine;
 - connecting said propeller to an engine shaft of said internal combustion
 - 10 engine;
 - measuring a speed of said engine shaft at a given throttle setting while said propeller is connected to said internal combustion engine; and
 - using said speed measurement and said power versus motor shaft speed characteristic of said motor to determine the power produced by said engine.
- 15 2. The method of claim 1, wherein the step of determining the power versus motor shaft speed characteristics further comprises the steps of:
 - connecting said propeller to said motor shaft of said electric motor; and
 - measuring the power required to produce a given motor shaft speed for a
 - 20 plurality of motor shaft speeds.
3. The method of claims 1 or 2, further comprising determining the power produced by said engine for a plurality of engine shaft speeds.
- 25 4. The method of any one of the previous claims, further comprising measuring a fuel flow rate for said engine for each of a plurality of propellers at a plurality of engine throttle settings.
5. The method of claim 4, wherein the step of measuring said fuel flow rate
- 30 further comprises:
 - measuring an initial mass of a fuel tank supplying fuel to said engine at a first time;
 - measuring the mass of said fuel tank again after a period of time;
 - calculating a change in mass of said fuel tank; and

dividing said change in mass by said period of time to determine said fuel flow rate.

6. The method of claims 4 or 5, wherein said fuel flow rate at said throttle setting and said engine power are used to calculate an efficiency for said engine.

7. The method of claim 6, wherein said engine efficiency is calculated using the formula $\eta = \frac{P}{\dot{m}_f Q}$, wherein η is said engine efficiency, P is said power produced by said engine, $\dot{m}_f$ is said fuel flow rate, and Q is a constant depending on a type of fuel being used.

8. The method of claim 7, further comprising:
calculating an efficiency curve for a plurality of propellers at a plurality of engine shaft speeds and engine throttle settings; and
selecting one of said plurality of propellers to meet a desired criteria.

9. The method of claim 8, wherein said desired criteria is one of a desired engine efficiency or a desired engine power.

10. The method of any one of the previous claims, wherein a tachometer is used to measure a speed of said propeller when connected to said engine shaft.

SYSTEM AND METHOD TO USE PROPELLERS AND ELECTRIC MOTORS TO MEASURE THE POWER PRODUCED BY INTERNAL COMBUSTION ENGINES

ABSTRACT

5 A method for determining a power produced by a internal combustion engine for use
in designing/selecting a propeller for the engine, the method comprising the steps of:
determining power versus motor shaft speed characteristics for at least one
propeller coupled to an electric motor having a similar power rating and motor speed
range as that of the internal combustion engine; connecting said propeller to said
10 internal combustion engine; measuring a speed of said propeller while connected to
said internal combustion engine; using said speed measurement and said power
versus propeller speed characteristic of said propeller to determine the power
produced by said engine. In some embodiments, a fuel flow rate and engine
efficiency may also be calculated, and these calculations used to design/select the
15 propeller.

FIGURE 5