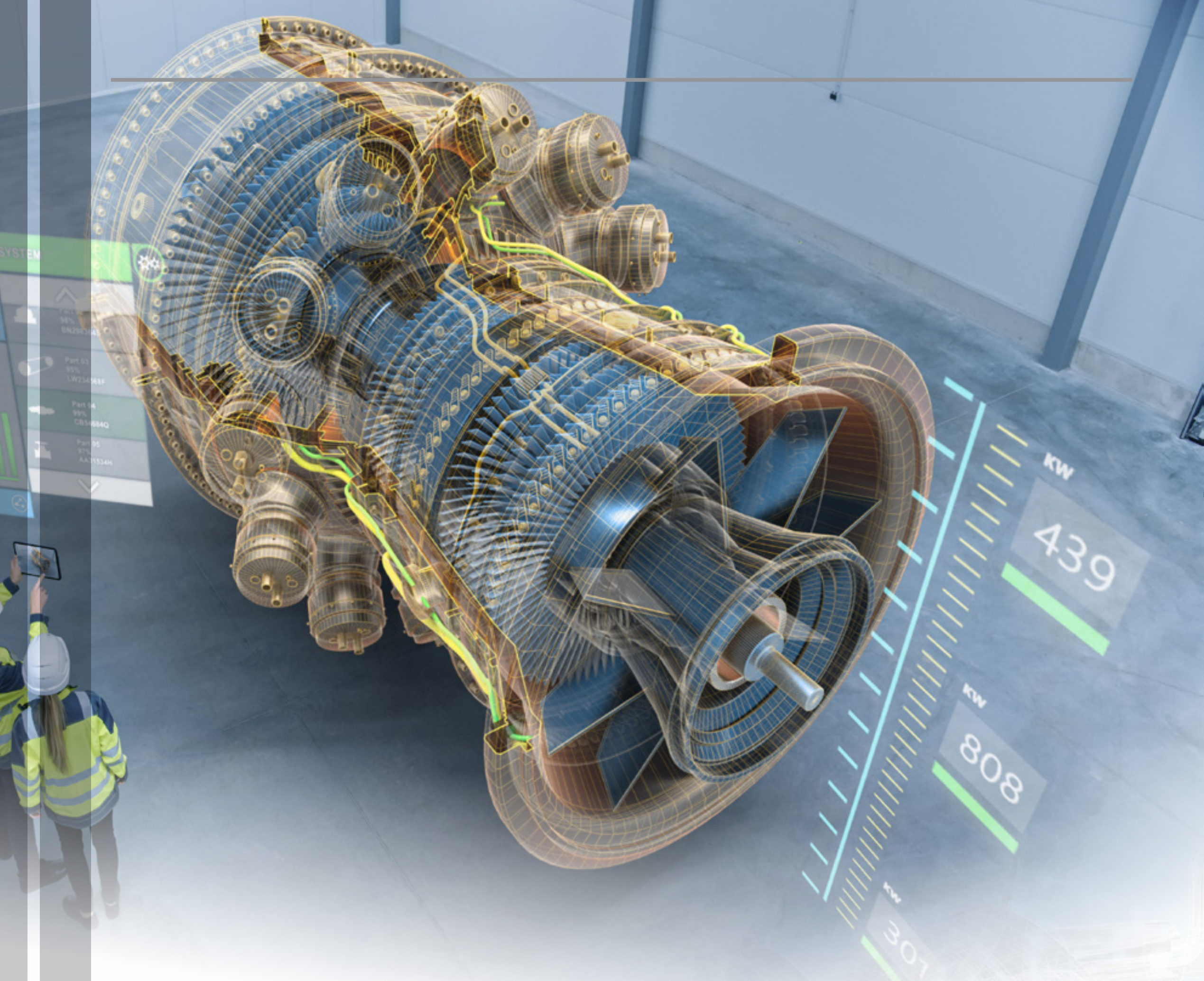
STEM LAB by UGEARS

MECHANICAL MODEL

TACHOMETER

Handbook of A Young Engineer

§1 Introduction



An engine or motor is a machine for converting some form of energy into mechanical energy. Much science and technology, especially the area of physics known as "mechanics," has developed in close relation to the invention and widespread implementation of engines in production and in everyday life. Engines also play an important role in transport.

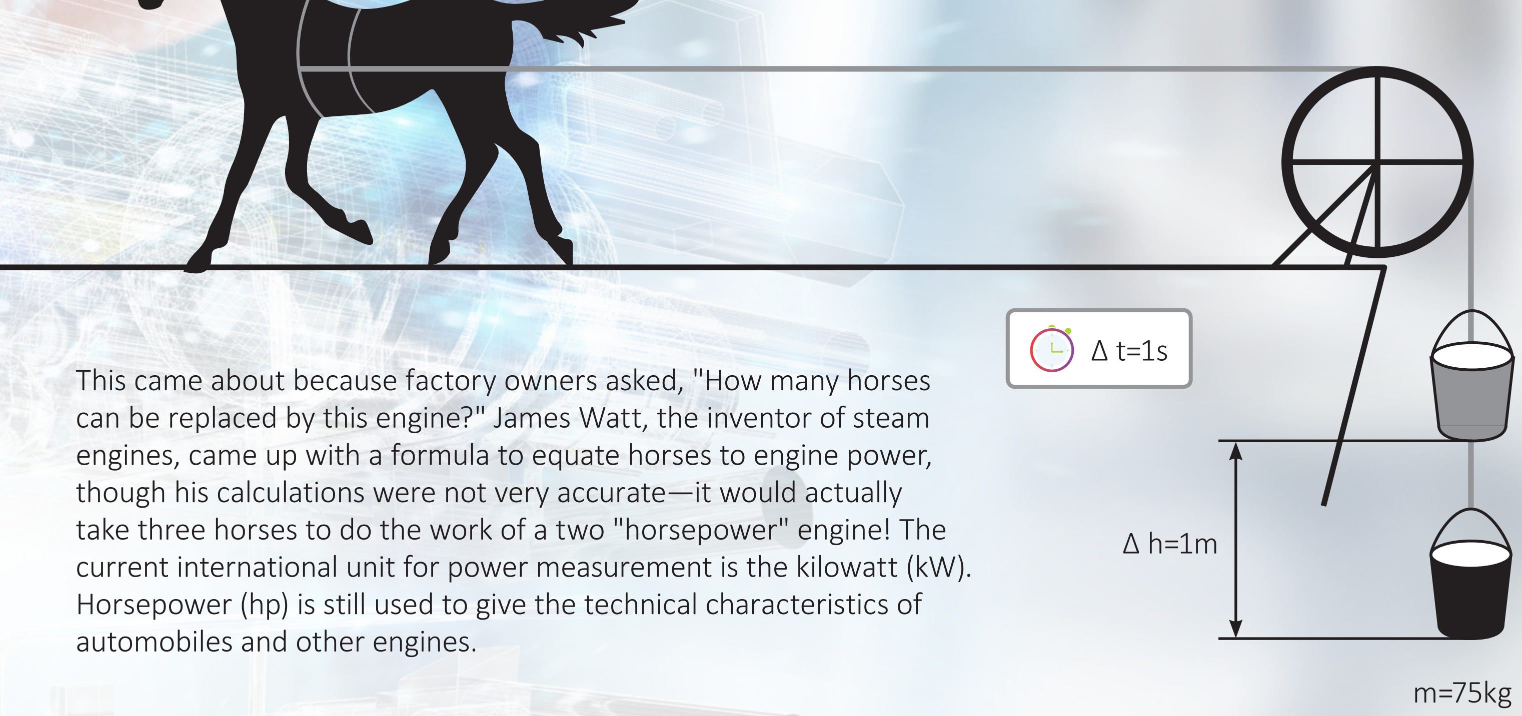
Engines are the basis for almost any mechanism or machine. The engineer's challenge is to not only create a simple and reliable mechanism, but to effectively control it. The shaft in a motor converts energy from the motor into the end use application. Motor control is achieved by controlling changes in shaft speed, and therefore torque (torque and speed are inversely proportional), which directly determines the engine's power.

Shaft speed is therefore an important parameter to measure during operation of a motor. One must know and monitor shaft speed for efficient engine operation. To do this, tachometers are used.

- *Power is the work done by an engine per unit of time. Power units: horsepower (hp), watt (W), kilowatt (kW).*

If power is indicated in horsepower you can easily calculate the power in kilowatts. To do this, simply divide the power in hp by 1.35.

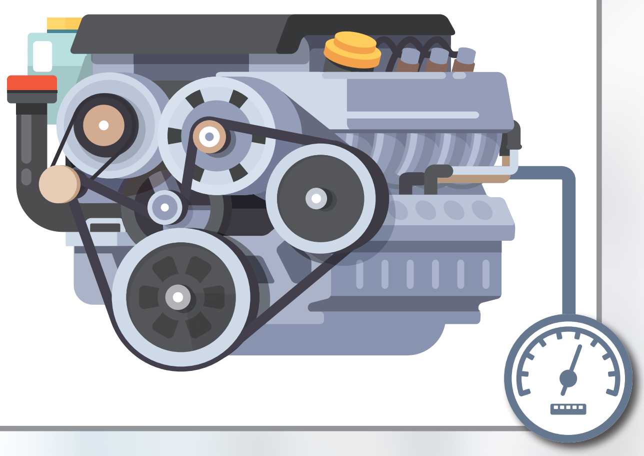
Historical background:
Since the 18th century, the unit of measurement for engine power has been horsepower.



This came about because factory owners asked, "How many horses can be replaced by this engine?" James Watt, the inventor of steam engines, came up with a formula to equate horses to engine power, though his calculations were not very accurate—it would actually take three horses to do the work of a two "horsepower" engine! The current international unit for power measurement is the kilowatt (kW). Horsepower (hp) is still used to give the technical characteristics of automobiles and other engines.

- Torque (moment of force) is a value equal to the product of force and the distance from the axis of rotation to the point of application of the force (a torque of 1 N*m corresponds to a force of 1 Newton applied at a distance of 1 meter from the axis of rotation). Units: Newton-meters (symbol: N*m).

- Rotational speed indicates the number of revolutions made by an engine shaft per unit of time. The rotational speed is measured in revolutions per minute, or revolutions per second (symbols: rpm, rps).



The measure of an engine's performance is torque. Engine power is attained by multiplying torque by RPMs. For most cars and stationary mechanisms, maximum engine power is the main parameter indicated, while other parameters are used less often. Engine power is typically not constant, but varies in non-linear fashion according to rotational speed (RPMs).

In order to chart these various parameters, engine characteristic curves are used. The engine characteristic is the relation between torque (or power) and rotational speed. For mass-produced engines that are used in industry and transport (e.g., electric motors, internal combustion engines), mechanical characteristics are obtained empirically. A typical characteristic of an internal combustion engine is shown in Fig. 1.

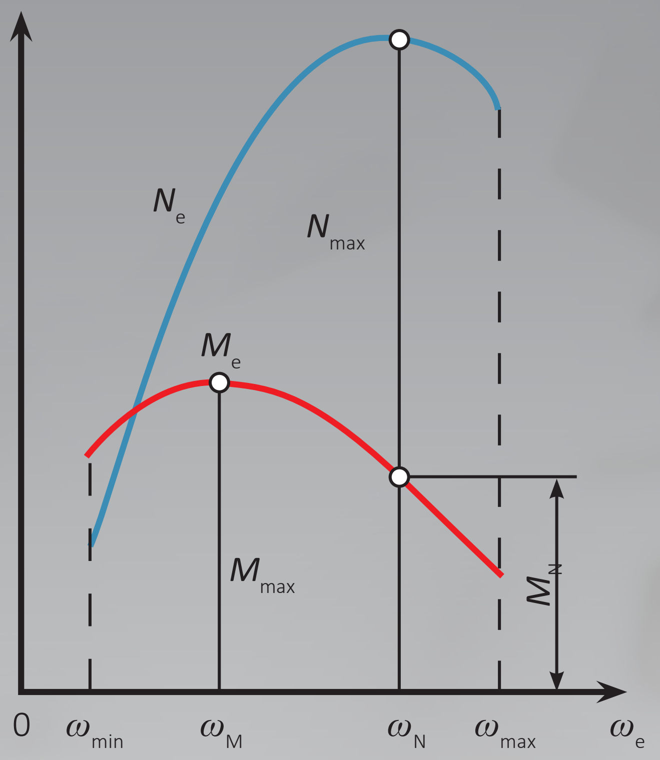
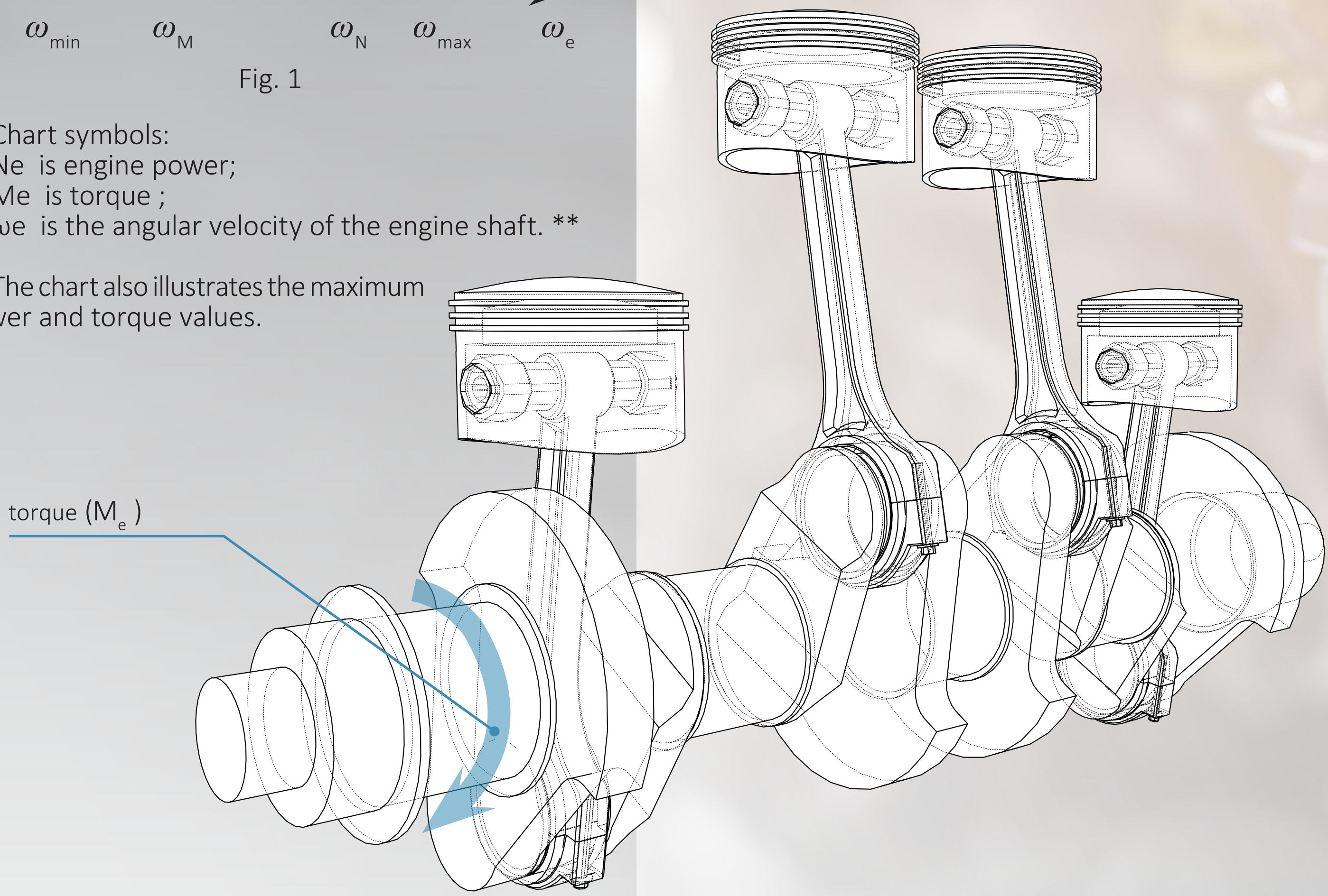


Fig. 1

Chart symbols:
Ne is engine power;
Me is torque ;
ωe is the angular velocity of the engine shaft. **

The chart also illustrates the maximum power and torque values.



ω is angular velocity.

In engineering calculations, rotational speed is often expressed in terms of angular velocity. Angular velocity is equal to the rate of rotation around an axis. It is measured in radians per second (rad/sec). Angular velocity is proportional to rotational speed according to the relationship:

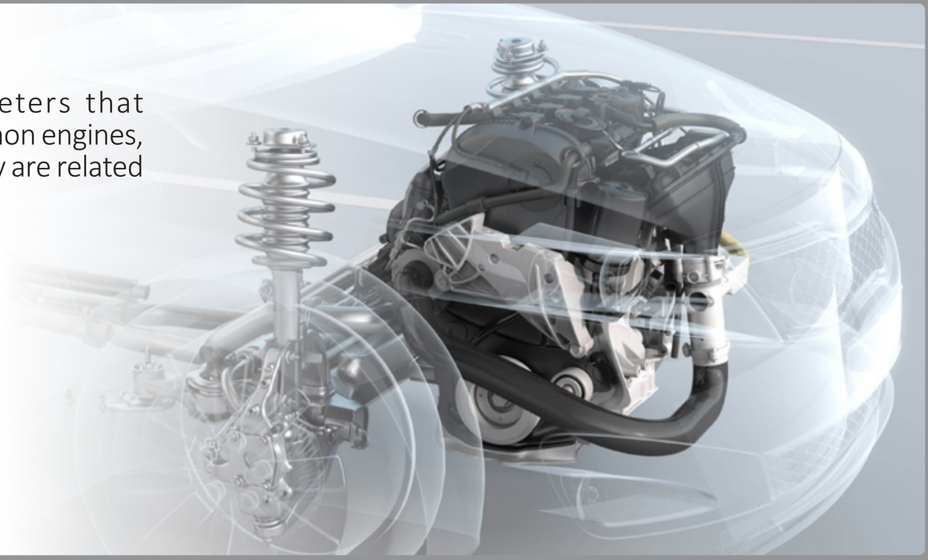
$$\omega = \frac{\pi \cdot n}{30}$$

where:
ω is the angular velocity;
n Is the rotational speed in rpm.

We've seen the primary parameters that characterize the operation of many common engines, where power, torque, and angular velocity are related to each other according to the formula:

$$N=M\cdot\omega$$

where N is the engine power;
M is the torque,
ω is the angular velocity.



It turns out that if you know just one engine parameter you can calculate all the rest.

It's difficult to measure engine torque. To do this, you need a special loading device, which doesn't allow measurement of this parameter while the engine is operating as part of the mechanism. Therefore, the optimal way to calculate an engine's parameters is to measure the rotational speed (angular velocity) of its shaft. Once that is obtained, engine power and torque can be calculated based on the engine characteristics.

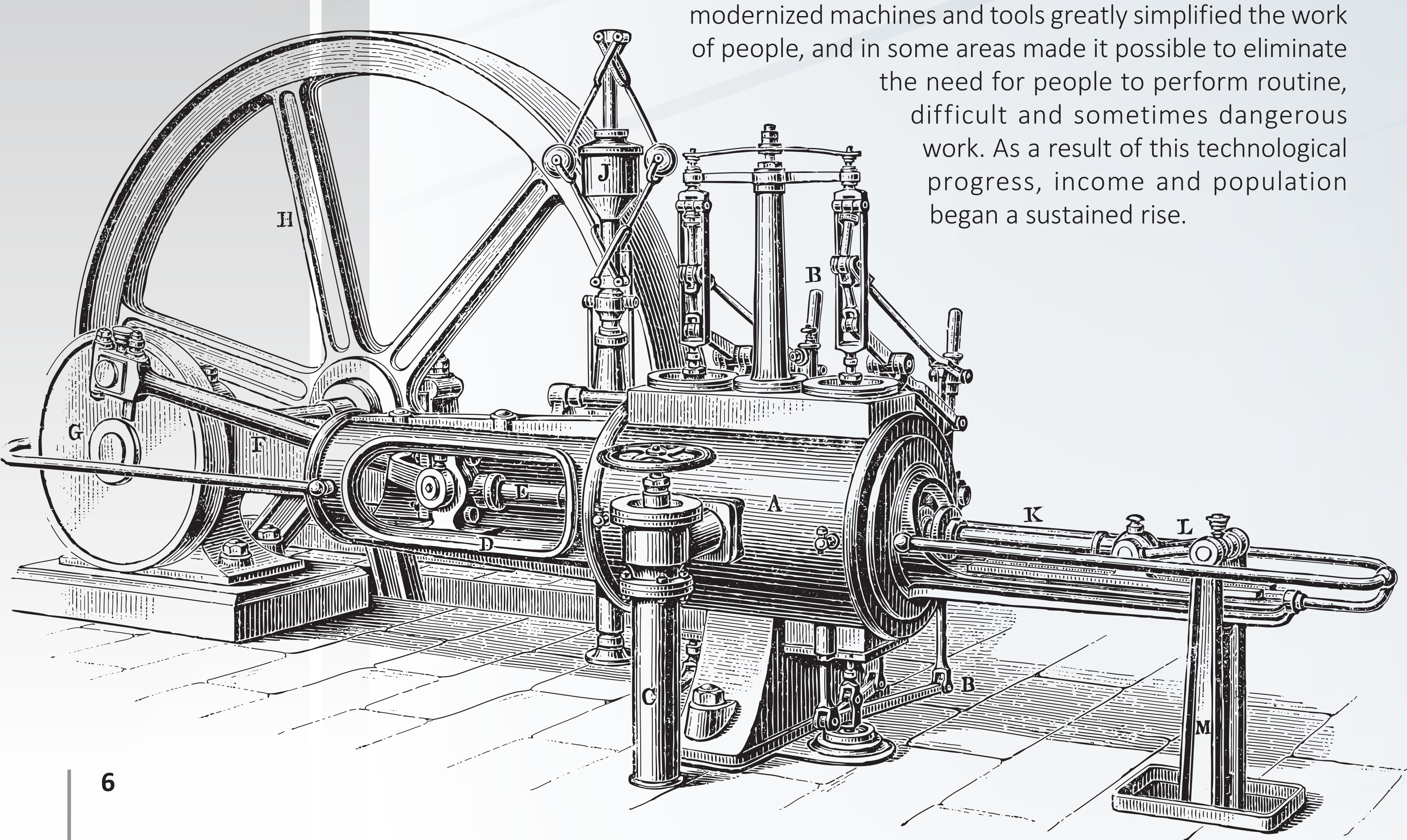
This method of calculating power is used not only for engines but also for mechanisms without engines, such as wind generators or hydraulic turbines that generate electrical energy.

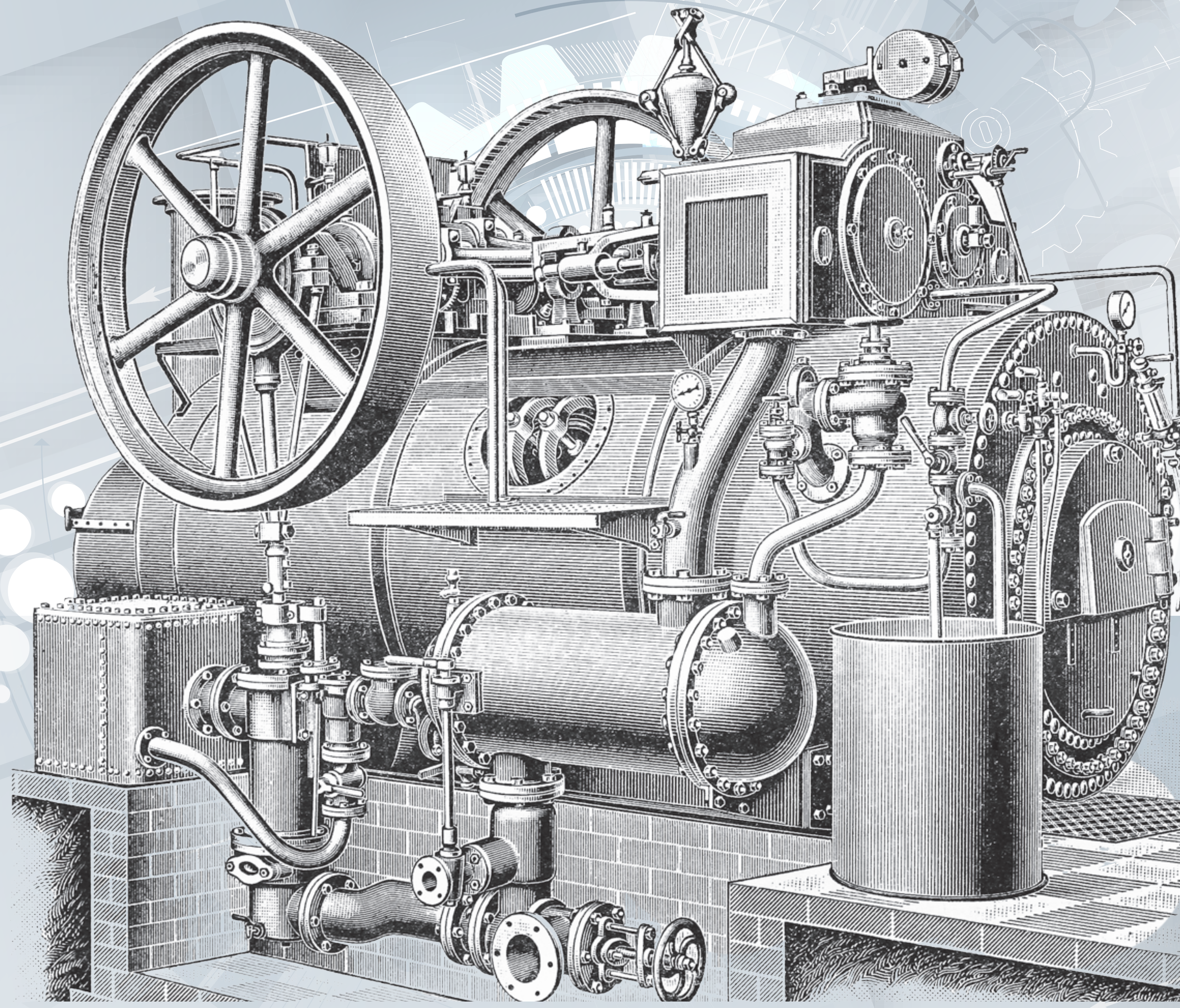
To measure rotational speed, **tachometers** are used.

A tachometer is a device designed to measure the rotational speed (number of revolutions per unit time) of various rotating parts, such as rotors, shafts, or discs, in various units, machines, and mechanisms.

§2 Historical background

With the invention of the steam engine, humankind began to move from hand production to factory-based machine production, which greatly accelerated the production process; this stage in human history is called the Industrial Revolution. The Industrial Revolution began at the end of the 18th century in Great Britain, where scientific research and new inventions significantly accelerated the transition to mechanized production. The introduction of various modernized machines and tools greatly simplified the work of people, and in some areas made it possible to eliminate the need for people to perform routine, difficult and sometimes dangerous work. As a result of this technological progress, income and population began a sustained rise.





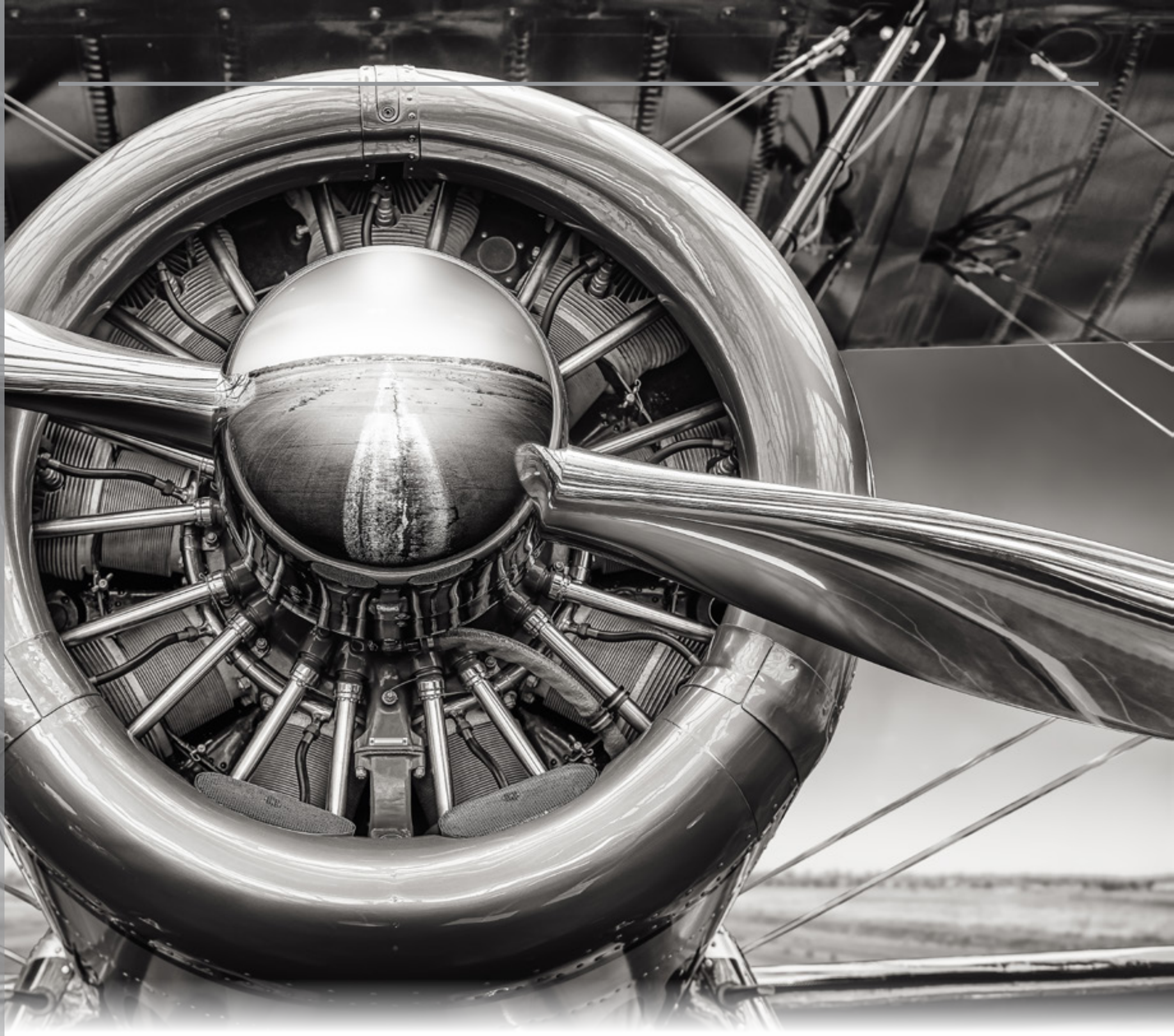
The appearance of the steam engine was a turning point in human history. The Industrial Revolution spread from Great Britain throughout Europe and the United States, bringing rapid urbanization and rapid economic growth to the western world. In just a few decades, these nations moved from an agrarian society to an industrial one.

As engines became more powerful, the need to accurately measure the rotational speed of their shafts became more urgent. But who invented the tachometer? This is where opinions differ.

Some historians claim that the first prototype of a modern tachometer was the brainchild of German engineer Dietrich Ulhorn, who in 1817 invented a special device to measure centrifugal force. In 1902, another German engineer—Otto Schulz—officially patented such a device. But another version (and this is widely accepted in the technical literature) has it that the parent of the tachometer was the American Curtis Widder, who presented his invention to the world in 1903.

At the beginning of its history and use, a tachometer was considered an expensive addition to a car. Today the tachometer is standard equipment on just about any car or motorized vehicle. In the mid-1930s, tachometers with light indicators appeared, and in the 1950s, electric ones became standard. But it is interesting to note that their displays have not changed much over the last century. In most cases motorists prefer the classic round tachometer dashboard display, simply because round devices are easier for the human eye to perceive and do not distract drivers from the road.

§3 What kind of mechanism is this? Where is it used?

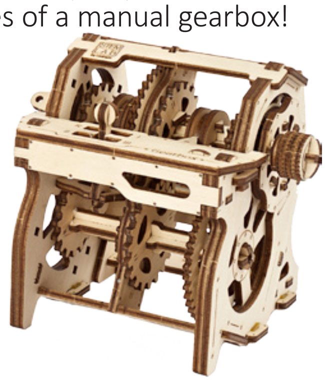


Steam engines, followed by internal combustion piston engines, transformed industry and manufacturing, and created opportunities for widespread water and air transport.

A steam engine is structurally simple and can work without a control system, due to the engine's principle of operation. It can operate efficiently at any shaft speed while still generating high torque.

The steam engine does not need additional accessories such as a gearbox, clutch or other auxiliary mechanisms, unlike internal combustion piston engines. But the efficiency of steam engines is low. This led to the internal combustion engine replacing the steam engine.

Check it out!
This is cool! If you want to find out how a gearbox works and how it is used, check out the Ugears "Gearbox" STEM-puzzle. It's a mechanical model that completely reproduces and demonstrates the operational principles of a manual gearbox!



In the modern world, internal combustion engines are used almost everywhere: in stationary machines, as well as in cars, ships, and, of course, airplanes. They are highly efficient but require additional control systems to ensure their proper operation.

A tachometer is a key component of an engine's control system. There are various types of tachometers. Modern monitoring and control systems use laser and electromagnetic sensors to measure rotational speed.

These are the best measuring methods in use today. The main advantage of these devices is their ability to carry out non-contact measurement. Laser revolution meters allow the sensor to be installed at any distance from the rotating shaft, making these devices quite versatile.

Electromagnetic sensors also allow non-contact measurement of rotational speed, but require additional components (usually permanent magnets) to be placed on the rotating shaft. In a magnetic system the magnetic components interact with a contactless sensor, but the distance between the sensor and the rotating shaft cannot be too great.

Modern non-contact measuring systems are simple, compact, reliable, and easily integrated into electronic control systems.

In the early days of engine manufacturing, there was no such thing as an electronic control system—electronic devices simply did not exist! Therefore, one needed to measure all the necessary engine parameters, as well as facilitate control, using mechanical devices.

Various mechanical sensors, as well as mechanical regulators (the simplest mechanical control systems), were developed and widely used. Mechanical devices only allow for a contact method to measure rotational speed, but engineers have made them quite compact and reliable.

The centrifugal tachometer and its application in transport and aviation

Tachometers usually consist of two connected components or modules. The first component is a sensor (sensing element) that directly measures rotational speed. The second component is a mechanical or electrical indicator (hand), which displays the readings of the device, either visually or in the form of electrical signals.

One of the first widespread devices for measuring rotational speed was the centrifugal tachometer

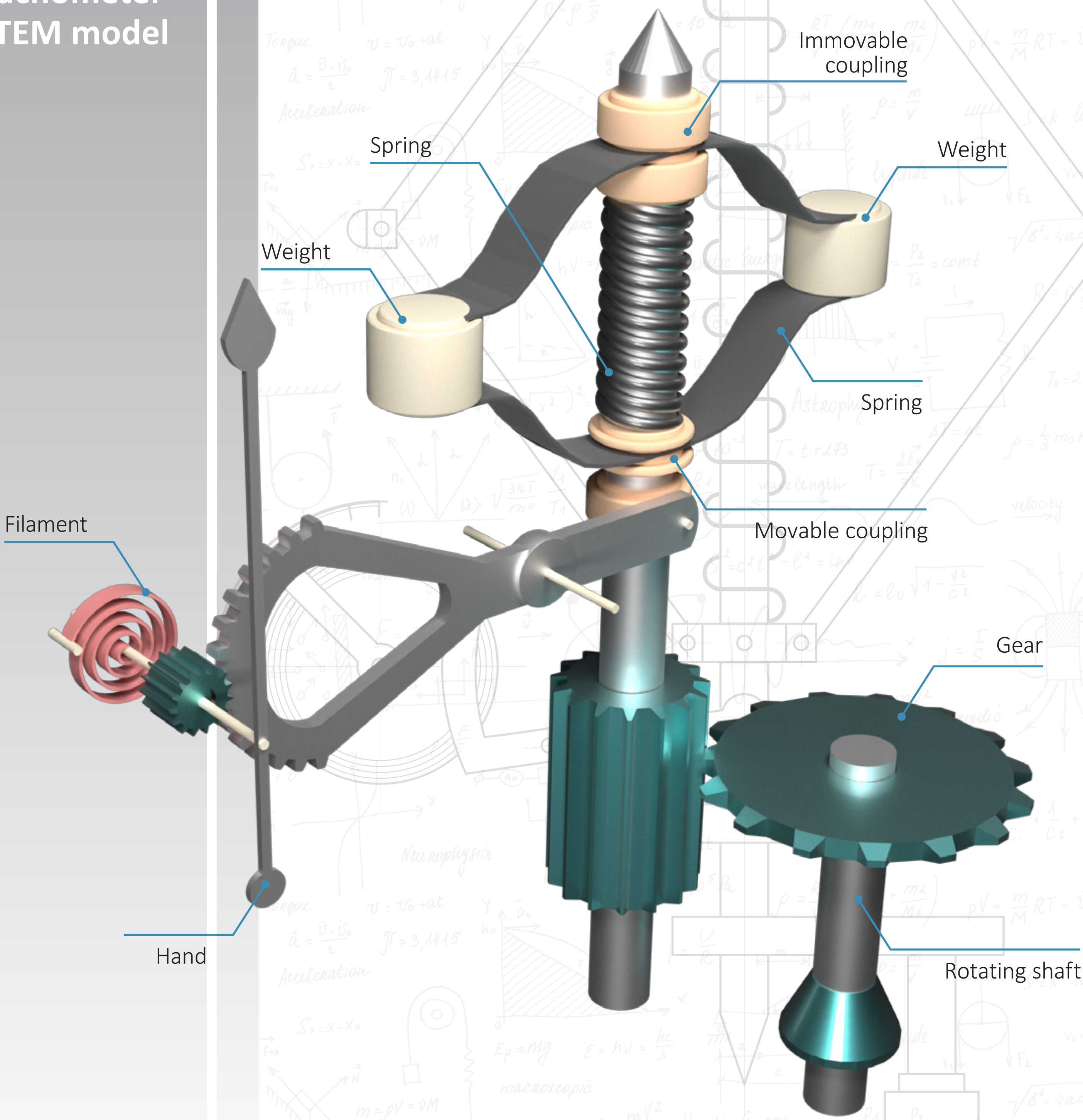


Fig. 2 Centrifugal tachometer scheme

FOR THE EXTRA CURIOUS!

Before we see how a centrifugal tachometer works, and how centrifugal force can drive an indicator hand, let's first take a look at what centrifugal force is, and how it arises.

If you take a weight, fix it on a thread and start rotating it, you will observe centrifugal force acting on the weight. Centrifugal force, by definition, is directed from the center (the axis around which the rotation occurs) to the periphery, and acts only on objects that rotate. This force is determined by the formula:

$$F = m \cdot a_ц;$$

where m is the weight mass;

$a_ц$ is the centripetal acceleration.

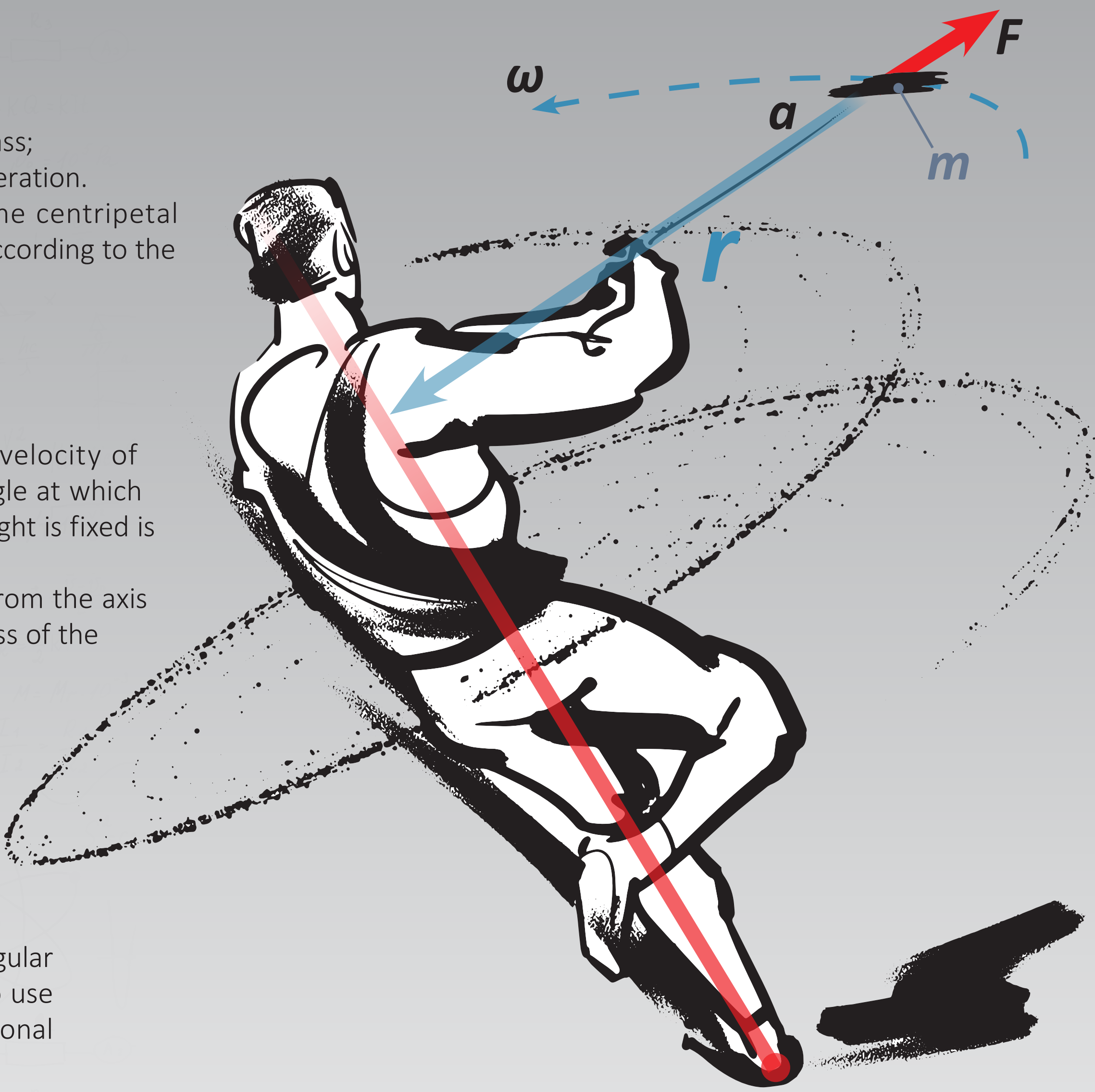
In the above formula, the centripetal acceleration can be found according to the relationship:

$$a_ц = \omega^2 \cdot r;$$

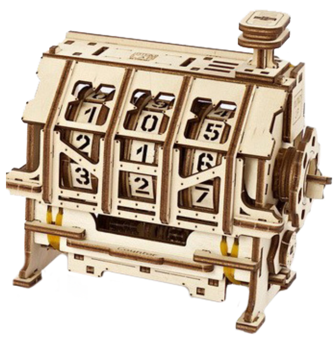
where ω is the angular velocity of the weight (showing the angle at which the thread on which the weight is fixed is rotated per unit time).

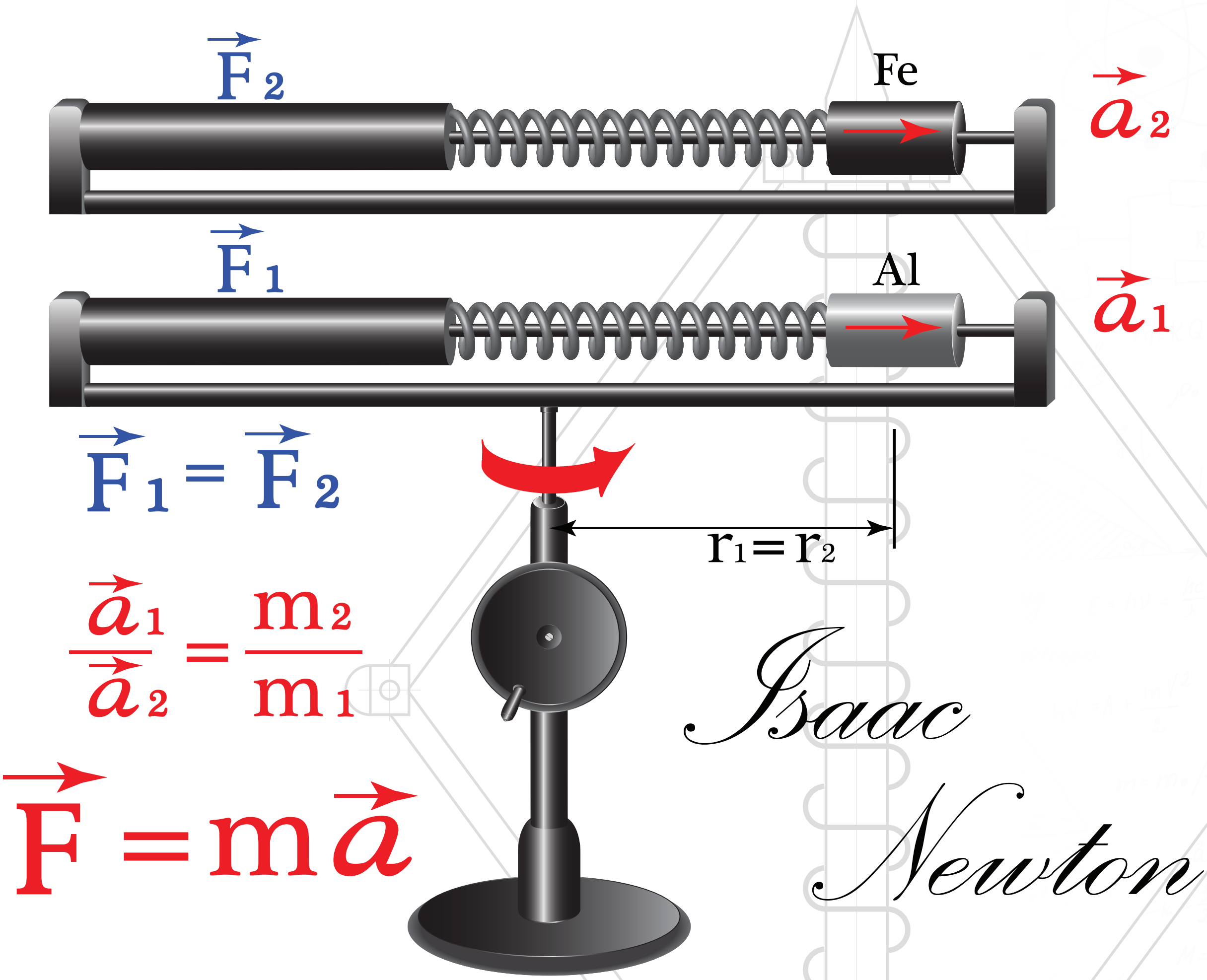
r is the radius (distance from the axis of rotation to the center mass of the weight).

Thus, the force will be proportional to the squared angular velocity. The relationship between the centrifugal force acting on any rotating body and angular velocity makes it possible to use this force to measure rotational speed.



Check it out!
You can find out how tachometers work in cars with the “Odometer” STEM-model from Ugears





The operating principle of a centrifugal tachometer is based on the effect of centrifugal force on weights placed on a rotating shaft, which are mechanically connected to the tachometer's indicator hand.

A centrifugal tachometer (Fig. 2) contains a rotating shaft (4), on which several weights (1) are located. These weights are acted upon by centrifugal force. As a rule, in tachometers the weights are placed symmetrically, and they interact with a spring. The centrifugal force and the restoring force of the spring (5) jointly affect the position of the movable coupling. The spring, in the absence of rotation, moves the coupling to its uppermost position.

Levers (2) transmit the centrifugal force from the weights to the spring. The lever system also links the rotating shaft to the movable coupling (3). This coupling rotates together with the shaft and simultaneously moves along the shaft. In this system, the resulting energy created by centrifugal forces compresses the spring, moving the movable coupling. Accordingly, the movement of the coupling is proportional to the shaft’s rotational speed.

In the absence of rotation, the coupling remains in its uppermost position (as shown in Fig. 2). When the shaft rotates with a certain rotational speed, under the influence of centrifugal force, the spring is compressed—in other words, the centrifugal force overcomes the restoring force of the spring. As rotational speed increases, the coupling moves downward in proportional to the speed.
Thus, by mechanically connecting the movable coupling with a sensor element (measuring device or hand) through a lever system (wires), the current number of revolutions can be transmitted to the control system of the engine, and/or displayed visually.

Greater deflection of the hand indicates greater centrifugal force, due to faster rotation. The tachometer hand will display the engine's rotational speed according to the device's scale.

Engine rotational speed must be measured not only in cars, but also in airplanes.

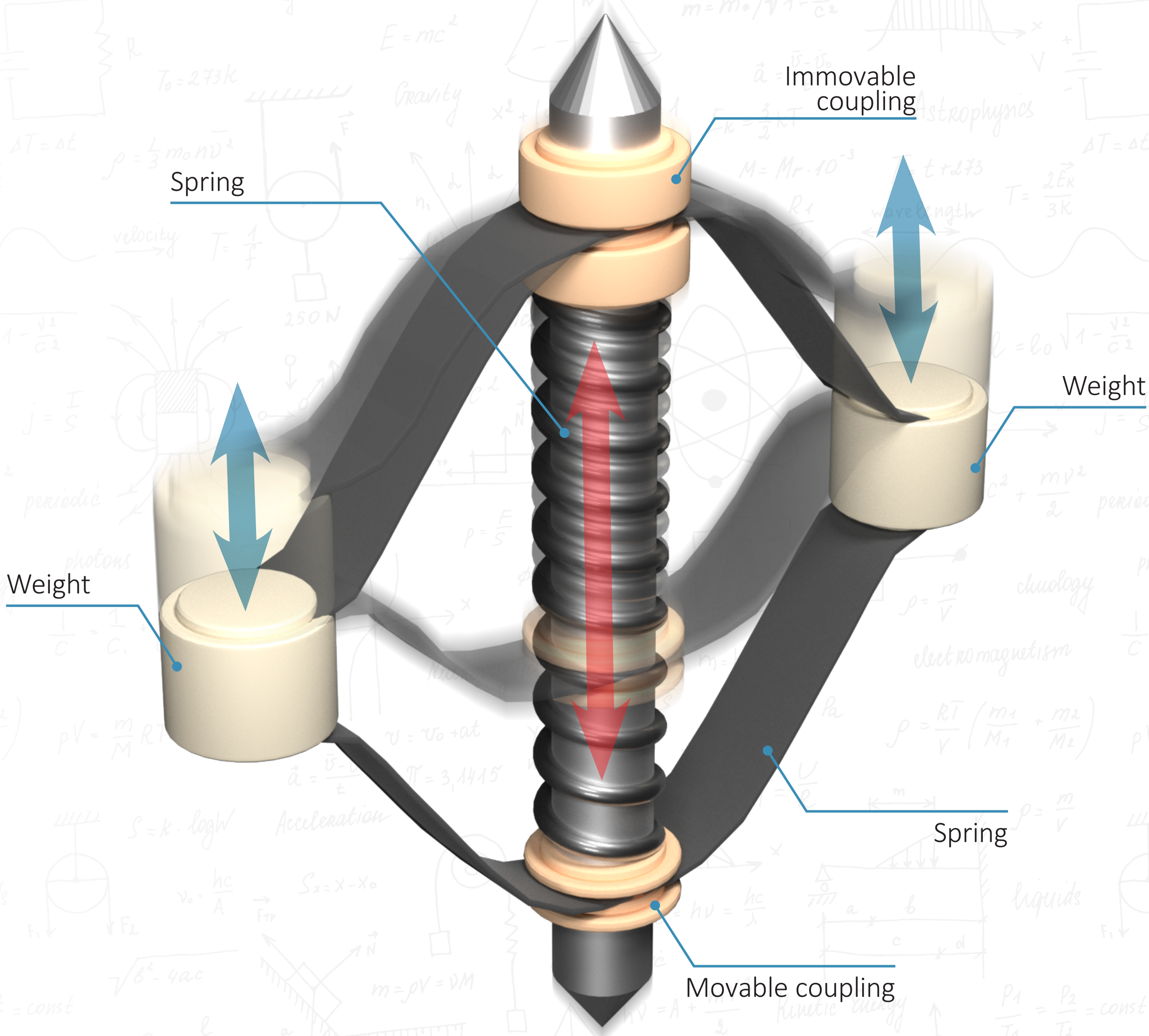
With aircraft, measuring RPMs is necessary for controlling the speed of the propeller. Small aircraft use a propeller driven by an engine. Aircraft typically use specially designed internal combustion piston engines such as radial engines (Fig. 3).

An airplane, unlike a car, does not have a gearbox and clutch. Immediately upon starting the engine (on a stationary aircraft), the propeller begins to rotate. But why does the plane remain stationary with a rotating propeller?

It's all about the revolutions. The propeller of an airplane creates thrust (pulling force) that causes the airplane to move along the runway or fly in the air. The thrust directly depends on rotational speed, but the relationship is complex: a twofold increase in rotational speed does not lead to a twofold increase in thrust.

After starting an aircraft engine, its shaft rotates at a low frequency (idle speed) such that the propeller creates only a slight thrust. The force is small and the plane remains stationary.

However, if you increase the propeller speed by only a few multiples, the thrust will increase sharply (Fig. 4).



In flight, it is desirable to keep a relatively constant propeller speed, to avoid exceeding the engine's operational limits. In smaller aircraft with fixed pitch propellers, higher air speed (e.g., in a dive, like a car going down a hill) will increase propeller speed as air rushes over the propeller. Similarly, lower air speed (e.g. in a climb, like a car going up a hill) will decrease propeller speed.

The pilot must compensate for these changes in air speed by increasing or decreasing the power delivered from the engine to the propeller. This is accomplished with a throttle, which controls the flow rate of the air-fuel mixture going into the engine.

More fuel provides more engine-generated thrust, and vice-versa. Accordingly, the pilot must keep an eye on the tachometer in order to avoid engine overload and to maintain relatively constant propeller speed.

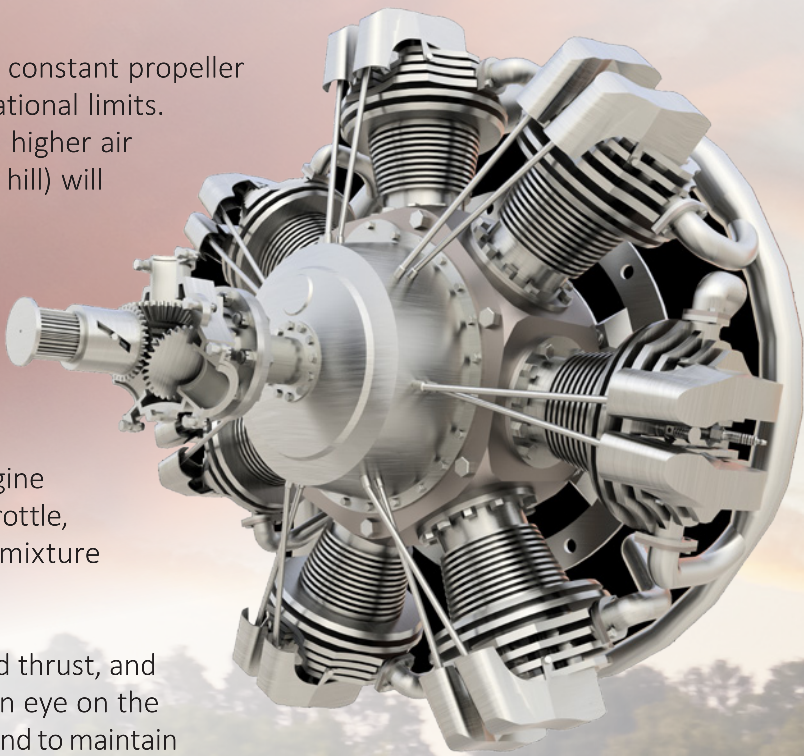


Fig. 3

The airplane is stationary (idle speed)

The airplane is flying at high speed (maximum rotational speed)

Fig. 4

Aircraft engine parameters also depend on the fuel supply to the engine, air humidity and density, current aircraft speed and many other factors. In more modern aircraft, variable pitch propellers allow the propellers to take a bigger "bite" of air, increasing thrust. A control system is used to maintain constant thrust and the ability to make precise adjustments to thrust. Nonetheless, an engine speed sensor, or tachometer, remains a key element of such systems.

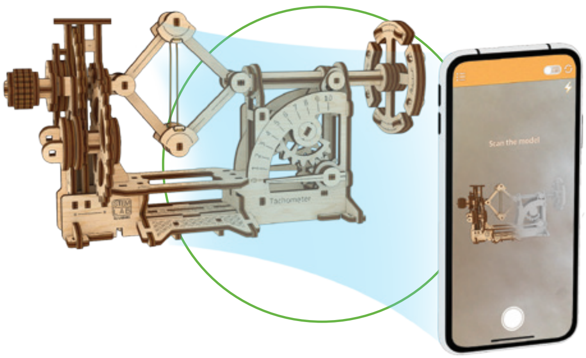
Early aircraft engine designs used compact centrifugal tachometers (which we discussed above), which were connected with an additional mechanism to the engine shaft. The mechanical connection made it possible to transmit rotation from the engine to the tachometer shaft, and its indicator hand showed current rotational speed. This made it possible to improve control of aircraft by manually adjusting the engine speed and thus the thrust generated by the propeller.

Unique AR-experience and real life usage

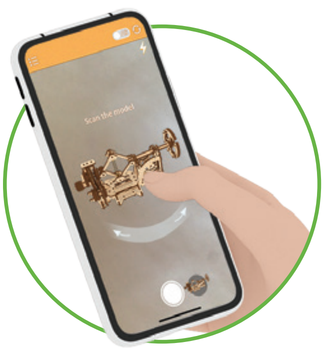
1 **Scan QR to download App**

2 **Open the application**

3 **Point and align the image on the screen with the model**



4 **Interact in AR**



A Ugears STEM-lab mechanical model is an interactive guide to how a mechanism works.

When you assemble the TACHOMETER you will discover how this mechanism works and its principles of operation.

Plunge into the exciting world of augmented reality with the UGEARS AR app to supplement your learning. Just point your smartphone or tablet at the assembled model to see how the mechanism is used in real life. You can interact with the model on the screen, see the mechanism from a variety of angles, and learn how the TACHOMETER is used in aircraft instrumentation.

ANDROID APP ON Google play

Available on the iPhone App Store

Enjoy our unlimited support!
Should you have any questions about assembly, we are always here for you to suggest the best solution and provide the help you might need. Our 24/7 customer support service will accept and process your request promptly and professionally.

Customer support:
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§5 Mechanics of the UGEARS centrifugal tachometer

The UGEARS tachometer's design follows the classic layout of a centrifugal tachometer (Fig. 5).

In our design, the tachometer shaft is driven by a special handle that transmits rotation to the shaft through a two-stage gear transmission.

There are two weights on the shaft, connected by means of levers. The weights are also interconnected by an elastic element.

The levers form a lever system that allows the centrifugal force created by the weights to slide the shaft along its axis. Thus, the distancing of the weights from the axis of rotation under the influence of centrifugal force leads to a corresponding horizontal displacement of the shaft along its axis using the lever system. In the absence of rotation, the shaft is in the leftmost position (Fig. 5).

However, when the shaft rotates, the weights create centrifugal force. By means of levers, the weights act on the shaft, moving it to the right along the axis (Fig. 6). In order to move the shaft, the centrifugal force must overcome the tensile force of the elastic element.

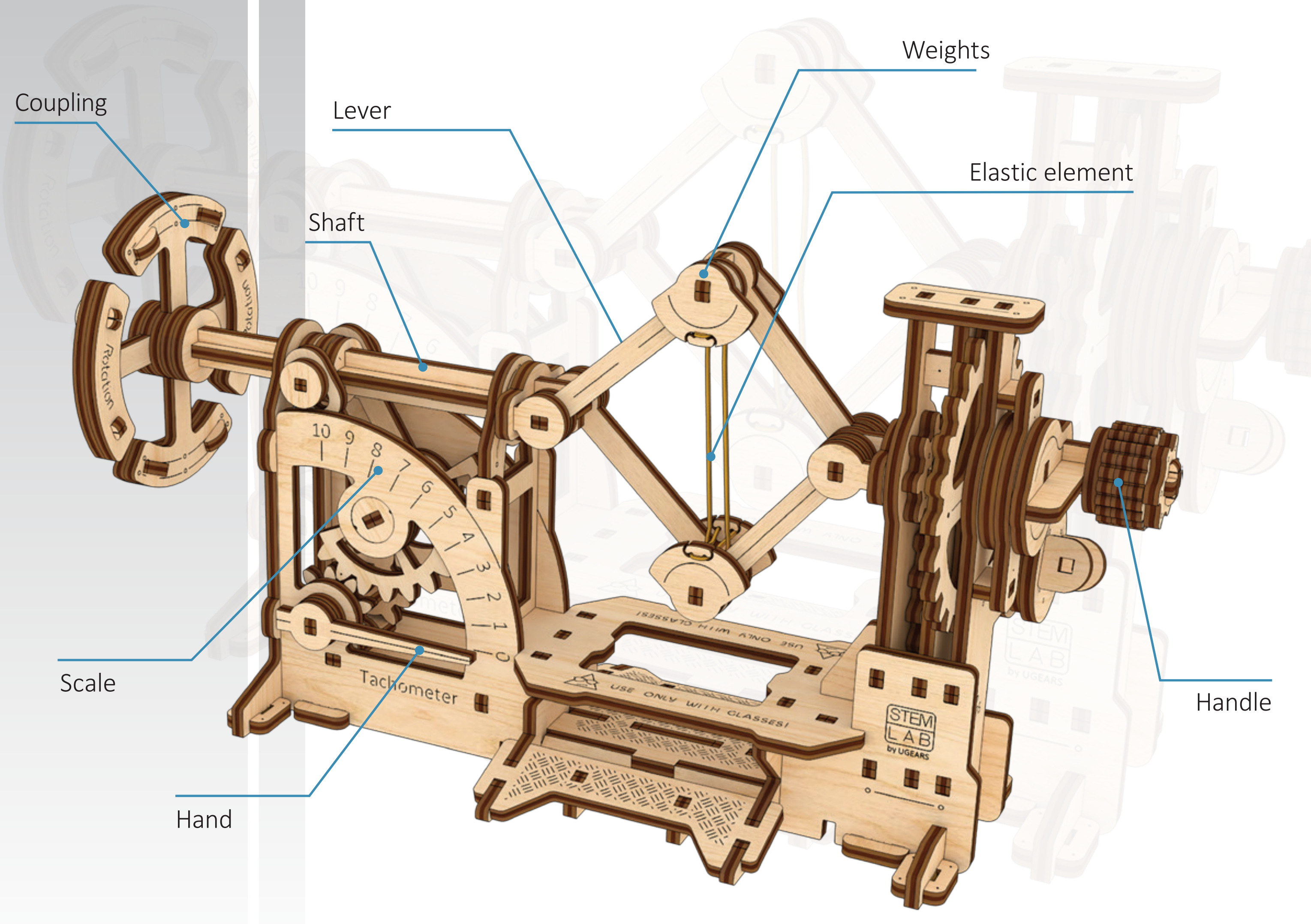

Fig. 5

CALIBRATION, MEASUREMENT OF ROTATIONAL SPEED WITH A UGEARS MECHANICAL TACHOMETER:

The device’s design requires significant centrifugal force to operate. At low speeds, the device will not overcome the strength of the elastic element and move the shaft.

Therefore, a gear transmission has been included in the design, to increase the rotational speed of the shaft.

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The elastic element obeys Hooke's law

Hooke's law states that deformation in an elastic body is proportional to the force applied to this body (the law was discovered by the English scientist Robert Hooke in 1660).

According to this law, the force created by the elastic element will be proportional to its tension. In our tachometer, higher rotational speed will correspond to a higher centrifugal force. As this centrifugal force increasingly overcomes the elastic's tensile force, you will observe increased movement of the tachometer shaft along its axis.

In the absence of centrifugal force, the shaft returns to its original position under the influence of the elastic element.

The tachometer shaft is connected to the tachometer's indicator hand by means of a coupling. The design of the coupling is such that it is connected to the shaft, but when the shaft rotates, the coupling does not rotate. The coupling will only move horizontally together with the shaft; accordingly, as the shaft moves along its axis by a certain distance, the coupling moves the same distance, with a corresponding rotation of the tachometer hand. This makes it possible to estimate the rotational speed of the tachometer shaft on the basis of the current readings of the hand.

Previously, we saw that the relation of centrifugal force to rotational speed is non-linear, but is instead proportional to the squared angular velocity, which somewhat limits the accuracy of the centrifugal tachometer.

This makes it necessary to properly calibrate the device. Calibration of devices such as a centrifugal tachometer can be accomplished if rotational speed is known in advance and can be adjusted. In order to provide a known rotational speed, the shaft can be driven by a separate machine with its own accurate tachometer. The centrifugal tachometer's reading for that known speed can then be determined and a mark inscribed on its scale. After that, a different speed is set, and a second mark is inscribed on the device's scale. The process is repeated until the desired number of marks is obtained, opposite each of which a number is inscribed indicating the shaft rotational speed.

You can perform an approximate calibration of the UGEARS tachometer using a stopwatch. Using the handle, rotate the shaft at a constant speed with the tachometer hand reading "2". At the same time, using a stopwatch, determine the time in which one revolution is completed on the handle. For example, if the stopwatch showed a rotational time of 1.5 seconds, we can calculate the rotational speed at 0.67 rps or 40 rpm. To improve accuracy, measure the time for 10 revolutions, then divide by ten. In our example, we now know that a rotational speed of 40 rpm corresponds to the tachometer's hand indication of "2". We also know that a reading of "0" corresponds to the absence of rotation of the shaft.

Measurements can be repeated, at different marks on the tachometer's indicator, e.g., next ascertain the rpm when the tachometer's hand reads "4". By performing a series of experiments you can calibrate the tachometer, establishing the relationship between the device's readings and current rotational speed. Three or four empiric readings should be enough to establish values for one extreme and two or three intermediate marks on the scale. The speed values for all other marks can be deduced accordingly. In this way, you can determine approximate rotational speed for any tachometer mark by reference to your "updated," calibrated scale for the device.

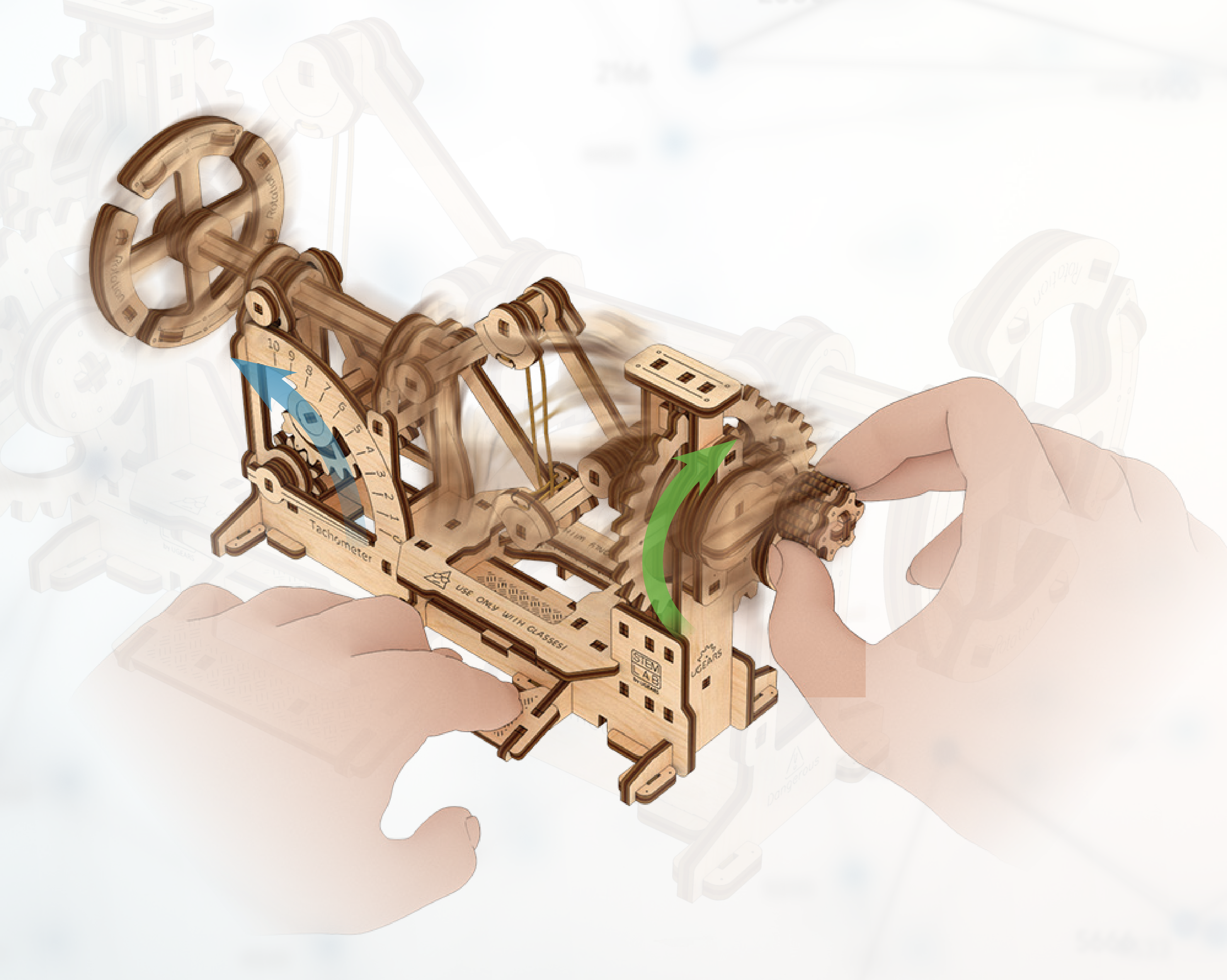

Fig. 6

TEST

1. The angular velocity of a shaft is:

☐ a) the number of shaft revolutions per unit of time
☐ b) the angle of rotation of the shaft per unit of time
☐ c) the time during which the shaft makes one revolution

2. To find out the engine power you need to:

☐ a) multiply the torque by the rotational speed
☐ b) multiply the torque by the angular velocity
☐ c) divide the torque by the angular velocity

3.A car's engine power is 100 horsepower. What is its power in kilowatts?

☐ a) 135 kW
☐ b) 200 kW
☐ c) 74 kW

4. The rotational speed of a propeller (engine shaft) is 6000 rpm. How long does it take for the engine shaft to complete 1 revolution?

☐ a) 0.01 seconds
☐ b) 0.06 seconds
☐ c) 0.1 seconds

Congratulations! You made it!

Thank you for being with us in this adventure, we hope you had fun and learned a thing or two!

Answers: 1.b, 2.b, 3.c, 4c.