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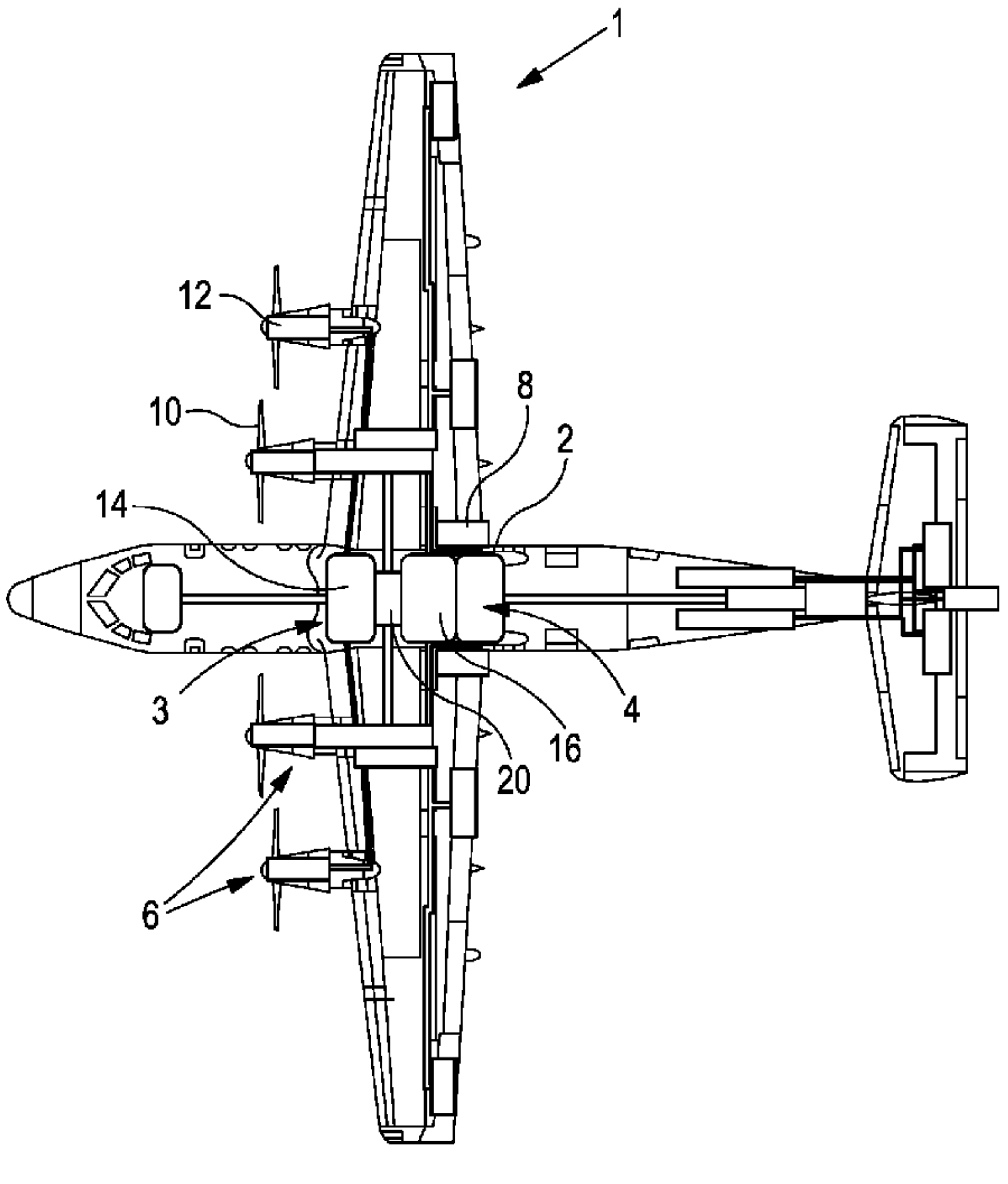

FIG. 1

(57) Abstract: An energy recovery system for an aircraft, an aircraft comprising such an energy recovery system and a method of energy recovery. The energy recovery system comprises: a transducer assembly arranged to selectively interact with one or more wheels of the aircraft to extract energy from the wheels; and an energy accumulator for storing the extracted energy.

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SYSTEMS AND METHODS FOR AIRCRAFT

The present invention relates to systems and methods for aircraft. In particular, the present invention relates to systems such as propulsion management systems, cooling systems and energy recovery systems, and associated methods.

BACKGROUND

An aircraft flight includes the following phases: taxiing to the runway; takeoff (which includes the takeoff roll); climb; cruise; descent; final approach; and landing (which includes the landing roll). In the taxiing phase, the aircraft moves to the runway under its own power. The aircraft is positioned on the runway ready for the takeoff roll. In takeoff, thrust from the aircraft propellers or jet engines accelerate the aircraft up to speed during a takeoff roll, and once a suitable speed is achieved the nose of the aircraft is raised to increase lift from the wings and effect take off. In the climb phase, the aircraft climbs to cruise altitude and the aircraft speed is gradually increased. In cruise, the aircraft flies at a required altitude and, typically, at a constant speed. In the descent phase, the aircraft altitude is reduced by increasing drag. In the final approach, the aircraft is aligned with the runway before landing. In the landing phase, the aircraft lands on the runway and performs the landing roll, in which the aircraft is decelerated.

Aircraft noise pollution is an important consideration in aeronautics. Considerable noise is produced by the aircraft and its components during the various phases of aircraft flight. Of particular importance in relation to noise pollution are the phases of takeoff, climb, descent and landing. During these phases, the aircraft may pass close to residential areas. It is therefore common for flying restrictions to be applied to airports. These restrictions often require a night period in which aircraft may not be scheduled to takeoff or land at the airport's runways.

Both propeller and jet aircraft produce large amounts of noise during takeoff and climb. In propeller aircraft, this is because the propellers are operating far from optimum efficiency as a result of the low air speed. In jet aircraft, a large source of takeoff noise is a result of the difference between the air speed and the speed of the jet leaving the engine, which creates turbulence. Aircraft vibrations as a result of the large thrust required during takeoff and climb also produce noise. Both types of aircraft also produce considerable noise during descent and landing. Air brakes may be employed to increase drag, resulting in turbulent air and the creation of noise. Angles of descent are typically shallow as the aircraft must maintain speed to ensure lift, whilst increasing drag through use of the air brakes.

Hybrid and electric aircraft are powered at least in part by batteries. In such aircraft, it is beneficial to monitor and maintain battery health during operation, which may involve monitoring the battery power level and temperature. Batteries under large loads typically require cooling. In hybrid aircraft, the power supply must be managed to ensure that it is being used most effectively. Refuelling aircraft, including charging batteries, conventionally takes place on the ground. Upon landing, aircraft wheel brakes may be applied, which creates significant heat which must be brought below a required temperature before subsequent takeoff. These factors increase “turnaround time”. Turnaround time is the time between landing and a subsequent takeoff, wherein the aircraft is not in operation. Decreasing turnaround time is of high importance to airlines.

Perhaps more generally, there is a drive to reduce pollution and other negative environmental impacts of aircraft and the aerospace industry as a whole.

It is an object of the present invention to provide improved systems for aircraft and/or to address one or more of the problems discussed above, or discussed elsewhere, or to at least provide alternative systems.

SUMMARY OF THE INVENTION

According to the present invention there is provided a propulsion management system, a cooling system an energy recovery system, and associated methods, as set forth in the appended claims. Other features of the invention will be apparent from the dependent claims, and the description which follows.

According to a first aspect of the present invention there is provided a propulsion management system for an aircraft, the aircraft comprising one or more wheels, and a ground propulsion system arranged to drive one or more wheels of the aircraft, the propulsion management system being arranged to control the ground propulsion system to drive the one or more wheels of the aircraft during a takeoff roll, the takeoff roll being subsequent to a taxiing phase.

Such a construction enables the aircraft to be accelerated during a takeoff roll using a ground propulsion system. This facilitates numerous advantages. An aircraft provided with a propulsion management system can take off in a shorter distance than a conventional aircraft. This allows the aircraft to takeoff from shorter runways, and also allows the aircraft to climb to altitude sooner, resulting in reduced noise at the ground. The ground propulsion system operates efficiently at low forward speeds, producing less noise than an air propulsion system, such as propellers, at low forward speeds. It is therefore well suited to the initial period of a takeoff roll and it is highly advantageous to provide a propulsion management system to control the ground propulsion system for such a purpose.

Driving the one or more wheels during a takeoff roll may mean driving the one or more wheels for more than 5%, 10%, 15%, or 50% of the runway length, total takeoff time, total takeoff distance. The propulsion management system may control the ground propulsion system to drive the aircraft to a speed of more than 40, 50, 60 or 70 knots.

The ground propulsion system may comprise an energy accumulator. The ground propulsion system may be powered by the energy accumulator. The energy accumulator may be a battery, a flywheel and/or a supercapacitor. Energy accumulators are advantageous as they may be provided with energy in a number of ways, facilitating energy recovery systems. Energy accumulators are also advantageous as they can have a small spatial footprint. Powering the ground propulsion system using the energy accumulator is advantageous as high power can be provided. Emissions are typically lower than for combustions engines.

The aircraft may comprise an air propulsion system. The propulsion management system may be arranged to control the air propulsion system. The air propulsion system may comprise one or more propellers or jet engines. The propulsion management system may be arranged to control the air propulsion system to drive the one or more propellers or jet engines. Air propulsion systems propel the aircraft in flight. The propulsion management system being arranged to control the air propulsion system and the ground propulsion system allows the propulsion management system to manage power distribution between the propulsion systems. Propellers are often best suited for domestic, or shorthaul, or regional, aircraft. Propellers also facilitate the provision of electric motors which may be powered by an energy accumulator.

A propeller pitch may be optimised for a climb phase. Optimising for the climb phase is advantageous as this is an energy intensive phase of flight. Climbing to altitude quickly helps to reduce noise pollution at ground level. The one or more propellers may be fixed pitch propellers. Fixed pitch propellers are simpler in construction than variable pitch propellers. Control systems are not needed, resulting in a cheaper, more reliable and lighter aircraft. Despite their advantages, fixed pitch propellers are typically not employed in commercial aircraft, as they are inefficient at low aircraft forward speeds. By providing a ground propulsion system, efficient operation of fixed pitch propellers is thus facilitated. A better overall balance is struck, based on the use of a ground propulsions system. Also, electrical driving of a fixed pitch propeller may be easier implement, or control, than the use of combustion engines, in terms of output torque and so on.

During a takeoff roll, the propulsion management system may be configured to cause the aircraft to move for a first time period using the ground propulsion system. The propulsion management system may be configured to cause the aircraft to move for a second time period using the air propulsion system. This facilitates a takeoff roll in which the aircraft initially travels along the runway using the ground propulsion system, and then using the air propulsion system. Overlap between the time periods result in faster acceleration, and therefore a sooner takeoff. No overlap between the time periods results in smoother acceleration, resulting in reduced aircraft vibrations and consequently a quieter takeoff, whilst providing a level of comfort to passengers or users. The first and second time periods may at least partially overlap. There may be an overlap time period during which the propulsion management system is configured to cause the aircraft to move using the ground propulsion system and the air propulsion system.

The propulsion management system may be arranged to cause the ground propulsion system to drive the aircraft wheels independently. Driving the wheels independently allows for the propulsion management system to distribute power independently between the wheels. This is advantageous where wheel slip occurs. This is also advantageous where the aircraft deviates off a desired line, for example when taking off in strong crosswind.

The propulsion management system may be arranged to receive a situational condition. The propulsion management system may be arranged to control the ground propulsion system to drive the aircraft wheels independently in response to the situational condition. The situational condition may comprise one or more of: wind-speed, wheel speed, travel path or trajectory. Such control, to take into account such conditions, is simply not possible without direct driving of the wheels. Instead, no such control is possible, or aerodynamic changes need to be implemented, which could comprise other aspect of control such as aerodynamic factors or settings for a takeoff.

The situational condition may comprise a runway condition. A runway condition may be representative of the condition of the runway. In particular, the runway condition may inform the propulsion management system that the runway is dry, wet, or icy. Providing the propulsion management system with this information is advantageous as it allows the propulsion management system to adapt control of the aircraft in response to the runway condition. For example, where the runway is wet or icy, the propulsion management system may look to smooth acceleration profiles, or command a lower level of instantaneous ground propulsion system motor torque to ensure wheel traction.

The propulsion management system may be arranged to monitor the speed of the one or more wheels. The propulsion management system may be arranged to cause drive to be apportioned between the aircraft wheels in response to the wheel speed. The propulsion management system thus ensures that the aircraft wheels do not slip, and maintain traction with the runway surface. Such control, to take into account such conditions, is simply not possible without direct driving of the wheels.

According to a second aspect of the present invention there is provided an aircraft comprising a propulsion management system according to the first aspect.

The aircraft may comprise body-mounted landing gear. Alternatively, the aircraft may comprise landing gear provided on struts extending from beneath the aircraft wings or nacelles.

According to a third aspect of the present invention there is provided a method of aircraft takeoff comprising the steps of:

a. providing an aircraft comprising one or more wheels and a ground propulsion system arranged to drive one or more wheels of the aircraft; and

b. controlling the ground propulsion system to drive the one or more wheels of the aircraft during a takeoff roll, the takeoff roll being subsequent to a taxiing phase.

The ground propulsion system may be controlled to drive the one or more wheels for a first time period from the start of the takeoff roll.

According to a fourth aspect of the present invention there is provided a propulsion management system for an aircraft, the aircraft comprising one or more wheels, a power supply, a ground propulsion system arranged to drive one or more wheels of the aircraft and an air propulsion system, the propulsion management system being arranged to apportion power from the power supply between the ground propulsion system and the air propulsion system.

Apportioning energy between the propulsion system is advantageous as it can lead to the power supply being used most efficiently or effectively. The propulsion management system can manage power apportionment for low noise takeoff, short takeoff, minimum energy usage or other requirements. It also simplifies pilot workload as the propulsion management system enables the aircraft to have the same cockpit control layout as in a conventional aircraft, as it can manage the apportionment autonomously, without input from the pilot. Additionally, the propulsion management system ensures safe operation of the aircraft systems.

The propulsion management system may be arranged to apportion power between the ground propulsion system and the air propulsion system during a takeoff roll. A significant amount of power is required during takeoff, and so apportioning energy effectively by using the propulsion management system is highly advantageous.

The propulsion management system may comprise a single actuator for the ground and air propulsion system. The propulsion management system may apportion power based on the level of actuation. Thus, the pilot need not focus on power apportionment. Additionally, a standard cockpit layout can be retained.

The propulsion management system may be arranged to monitor the energy potential of the power supply. Energy potential may include battery charge level or fuel level. It is advantageous for the propulsion management system to be provided with this information such that it can make informed decisions on how to use the power supply most effectively.

The power supply may comprise an energy accumulator and an internal combustion engine. The propulsion management system may be arranged to apportion the supply of power from the energy accumulator and the internal combustion engine. This facilitates efficient use of power. For example, where the battery charge is high, it may be preferable to use the battery to power the propulsion systems. This creates battery "space" which may allow it to be used for energy recovery purposes. On the other hand, if the battery charge is low, the propulsion management system may prioritise battery charging, and operate the internal combustion engine to supply power to the aircraft. Where maximum power is required, the propulsion management system may demand a supply of power from both power sources.

The propulsion management system may be configured to control the supply of power from the power supply, in dependence on flight information (for example, automatically accessed by, or provided to, the system). The flight information may be one or more of:

a. Acceleration profiles stored in memory which result in: the quietest possible takeoff, the shortest possible takeoff, minimum power usage for takeoff, the smoothest possible acceleration, suitable levels of torque being applied to the wheels to ensure traction with the runway surface is maintained;

b. Deceleration profiles stored in memory which result in: the quietest possible landing, the shortest possible landing, minimum power usage to slow the aircraft, the smoothest possible deceleration, suitable levels of torque being applied to the wheels to ensure traction with the runway surface is maintained;

c. Power source management requirements, including: preserving battery charge, using excess charge to make capacity for regeneration (including decelerating the aircraft using the energy recovery systems), using excess fuel, battery temperature;

d. Flight plan information, including: the distance to the destination, time to destination, turnaround time at destination;

e. Airport data, including: runway length at takeoff airport or at destination airport, availability of charging ports at destination; or

f. Situational conditions, including: wind speed, wheel speed, travel path and trajectory of the aircraft.

Providing such flight information is highly advantageous. Acceleration profiles allow the propulsion management system to apportion power, or use the power supply, in such a manner as to achieve the acceleration profile, which may be an optimum acceleration profile for purpose, such as quiet or short takeoff or minimum power usage. Providing deceleration profiles are similarly advantageous. Flight plan information allows the propulsion management system to apportion power based on journey requirements, and may, for example, look to preserve battery charge if turnaround time at destination is intended to be short.

The propulsion management system may be configured to apportion power from the power supply between the ground propulsion system and the air propulsion system based on a required take-off, flight, or landing condition.

According to a fifth aspect of the present invention there is provided an aircraft comprising a propulsion management system according to the fourth aspect.

The aircraft may comprise body-mounted landing gear. Alternatively, the aircraft may comprise landing gear provided on struts extending from beneath the aircraft wings or nacelles.

According to a sixth aspect of the present invention there is provided a method of managing propulsion in an aircraft, the method comprising the steps of:

a. providing an aircraft comprising one or more wheels, a power supply, a ground propulsion system arranged to drive one or more wheels of the aircraft, and an air propulsion system; and

b. apportioning power from the power supply between the ground propulsion system and the air propulsion system.

The step of apportioning power may comprise:

a. powering the air propulsion system to drive the one or more propellers of the aircraft; and

b. not powering the ground propulsion system.

Not powering the ground propulsion system may be advantageous to ensure smooth acceleration, or once the aircraft is travelling at a speed which leads to more efficient air propulsion system operation.

The step of apportioning power may comprise:

a. powering the ground propulsion system to drive the one or more wheels of the aircraft; and

b. simultaneously powering the air propulsion system to drive the one or more propellers of the aircraft.

Simultaneously powering the ground and air propulsion systems facilitates maximum acceleration.

Power may be apportioned to the ground propulsion system to drive the one or more wheels of the aircraft until a threshold aircraft speed is achieved. The threshold aircraft speed may be one where the air propulsion system will operate above a certain level of efficiency. The step of apportioning power may be during a takeoff roll or landing roll.

According to a seventh aspect of the present invention there is provided an energy recovery system for an aircraft, the energy recovery system comprising: a transducer assembly arranged to selectively interact with one or more wheels of the aircraft to extract energy from the wheels; and an energy accumulator for storing the extracted energy.

A substantial amount of energy is available for extraction from the aircraft wheels when they are in motion. In particular, during a landing roll, friction brakes heat up significantly. By providing an energy recovery system, this energy may be recovered and used, or stored in an energy accumulator. The energy recovered and stored can be used for subsequent operations and can alleviate the need to charge or supply power to the energy accumulator. This can help to reduce turnaround time.

The energy accumulator may be a battery, flywheel or supercapacitor. The transducer assembly may be arranged to convert energy from the wheels into electrical energy. Electrical energy can be advantageously used to charge a battery. The transducer assembly may be arranged to convert rotational kinetic energy into electrical energy.

The energy recovery system may be operated during a landing roll. As previously mentioned, a substantial amount of energy is available for extraction during a landing roll, resulting from the high kinetic energy of fast rotating aircraft wheels.

The energy recovery system may be operated to provide braking effort during a landing roll. Such a construction is advantageous as it reduces heating of the wheels or any brake pads, recovers energy for subsequent use, as well as providing an easily controllable braking effort.

The energy accumulator may comprise a battery. The energy accumulator may be comprised in a power supply for a propulsion system of the aircraft. The recovered energy can thus be used to power the aircraft propulsion system.

The propulsion system may comprise a ground propulsion system arranged to drive one or more wheels of the aircraft. The transducer assembly may comprise one or more electric motors. The one or more motors may be arranged to drive the one or more wheels of the aircraft. The electric motors may be operated in reverse during operation of the energy recovery system. A ground propulsion system is advantageous for efficient aircraft takeoff and energy recovery on landing.

The transducer assembly may be selectively engageable with the one or more wheels. The energy recovery system may cause the transducer assembly to selectively engage with the one or more wheels. The level of braking force applied to each wheel is thus controllable, ensuring safe deceleration with no skidding, and also ensuring efficient energy recovery. The transducer assembly may be engaged during a landing roll.

According to an eighth aspect of the present invention there is provided an aircraft comprising an energy recovery system according to the seventh aspect of the present invention.

The aircraft may comprise body-mounted landing gear. Alternatively, the aircraft may comprise landing gear provided on struts extending from beneath the aircraft wings or nacelles.

According to a ninth aspect of the present invention there is provided a method of energy recovery in an aircraft, the method comprising the steps of:

a. interacting a transducer assembly with one or more wheels of the aircraft to extract energy from the wheels; and
b. storing the extracted energy in an energy accumulator.

The transducer assembly may convert energy from the wheels into electrical energy.

According to a tenth aspect of the present invention there is provided an energy recovery system for an aircraft, the energy recovery system comprising: a transducer assembly arranged to selectively interact with one or more propellers of a propulsion system of the aircraft to extract energy from the propellers.

Extracting energy from the propellers increases aircraft drag, allowing the aircraft to descend. By providing such an energy recovery system, the level of energy extraction allows the angle of descent to be controlled. A steep angle of descent is facilitated, which is advantageous in reducing noise levels at the ground. Extracting energy from the propellers also helps to slow the aircraft. Use of airbrakes can thus be minimised. Airbrakes create noisy turbulent air, so minimising their use is advantageous.

The energy recovery system may comprise an energy accumulator for storing the extracted energy. Storing the extracted energy in an energy accumulator allows the energy to be used for other tasks. The stored energy may, for example, be used for subsequent takeoff procedures where energy is extracted during a preceding descent. This reduces turnaround time at the destination airport as it is not necessary to charge the battery on the ground. Alternatively, the energy may not be stored, and may simply be used to power components of the aircraft.

The energy accumulator may be comprised in a power supply for the propulsion system of the aircraft. The energy accumulator may be a battery, a flywheel and/or a supercapacitor.

The transducer assembly may be arranged to convert kinetic energy into electrical energy. The transducer assembly may be arranged to control the rotational speed of the one or more propellers. Controlling the rotational speed provides a control of aircraft drag. Increasing drag results in an increased descent angle, which is advantageous in reducing overhead noise. The propeller rotation may be slowed significantly so as to reduce energy expenditure, or, to recover energy.

The transducer assembly may be arranged to inhibit motion of the one or more propellers. That is, the propellers may “windmill” or freely rotate. The transducer assembly may inhibit the free rotation. The level of inhibition of the propellers can be controlled so as to provide a desired level of battery charging.

The energy recovery system may be operated to increase aircraft drag during a descent. Controlling the rotational speed provides a control of aircraft drag. Increasing drag results in an increased descent angle, which is advantageous in reducing overhead noise.

One or more of the propellers may be fixed pitch propellers. Fixed pitch propellers are simple to construct and maintain. They are also lighter and do not require complex control systems.

According to an eleventh aspect of the present invention there is provided an aircraft comprising an energy recovery system according to the tenth aspect of the present invention.

The aircraft may comprise body-mounted landing gear. Alternatively, the aircraft may comprise landing gear provided on struts extending from beneath the aircraft wings or nacelles.

According to a twelfth aspect of the present invention there is provided a method of energy recovery in an aircraft, the method comprising the steps of:

a. interacting a transducer assembly with one or more propellers of a propulsion system of the aircraft; and

b. extracting energy from the propellers.

The extracted energy may be stored in an energy accumulator. The level of energy extraction may be controlled so as to variably inhibit rotation of the one or more propellers, such that aircraft drag is controllable during a descent. The one or more propellers that the transducer assembly is not interacting with may be driven. The one or more propellers that the transducer assembly is interacting with may not be driven.

According to a thirteenth aspect of the present invention there is provided a propulsion management system for an aircraft, the aircraft comprising an air propulsion system having one or more propellers, the propulsion management system being arranged to control the air propulsion system to drive the one or more propellers in reverse in order to provide a reverse thrust.

Providing a reverse thrust is highly advantageous in rapidly decelerating the aircraft. This may advantageously be employed during a landing roll, or in the event of an emergency during takeoff.

The propulsion management system may be arranged to control the air propulsion system to drive propellers in reverse during a landing roll. This allows the aircraft to land on short runways, such as in cities or on aircraft carriers. Being able to rapidly bring the aircraft to a halt during a landing roll is also a useful safety feature.

The pitch of a fixed or variable pitch propeller may be optimised to provide a desired or necessary level of reverse thrust. A necessary level may be one that provides maximum deceleration, or deceleration that brings the aircraft to a halt in a predetermined distance. The air propulsion system may comprise one or more electric motors drivingly connected to the one or more propellers. The air propulsion system motors may thus be used to drive the propellers, which facilitates simple construction in which only a single set of motors are required for both forward and reverse thrust. Electrically drive propellers may, in general, be far easier to operate in reverse than combustion-engine driven propellers, for example requiring little or no mechanical implementation to achieve. Electrical control may be simpler and more direct.

The aircraft may further comprise one or more wheels and a load assembly, and the propulsion management system may be operable to cause the load assembly to apply a load to the wheels of the aircraft to provide a braking effort during a landing roll. The load assembly may be a transducer assembly arranged to interact with one or more wheels of the aircraft to convert energy from the wheels into electrical energy. The electrical energy from the transducer may be supplied to the air propulsion system. Braking of the aircraft as a result of the load assembly will thus recover energy, which is advantageously provided to the propellers for increased braking by reverse thrust. Such a construction may partially or completely remove the need to provide a separate power source to achieve reverse thrust. The electrical energy may be supplied to a power supply for the air propulsion system.

According to a fourteenth aspect of the present invention there is provided an aircraft comprising an energy recovery system according to the thirteenth aspect of the present invention.

The aircraft may comprise body-mounted landing gear. Alternatively, the aircraft may comprise landing gear provided on struts extending from beneath the aircraft wings or nacelles.

According to a fifteenth aspect of the present invention there is provided a method of decelerating an aircraft, the aircraft comprising an air propulsion system comprising one or more propellers, the method comprising the step of:

a. operating the propellers in reverse to provide reverse thrust.

The propellers may be operated in reverse to provide reverse thrust during a landing roll. Operating in reverse means reversing the rotational direction of the propellers from a rotational direction that produces forward thrust.

The method may further comprise a step of adjusting the propeller pitch to provide a desired or necessary level of reverse thrust.

The aircraft may further comprise one or more wheels and a transducer assembly arranged to interact with one or more wheels of the aircraft to convert energy from the wheels into electrical energy during a landing roll, thereby providing a braking effort to the aircraft. The method may further comprise the step of: supplying the electrical energy to a power supply for the air propulsion system.

According to a sixteenth aspect of the present invention there is provided a cooling system for cooling a battery in an aircraft using a flow of gas, the cooling system comprising: an inlet, an outlet, and a gas flow path extending between the inlet and outlet, and at least proximal to the battery to cool the battery, and a transducer provided in the flow path, the transducer arranged to convert energy of the gas flow into electrical energy.

Such a construction enables thermal management of the battery, and simultaneous energy recovery. Substantial energy subsists in the gas flow (e.g. when the aircraft is in flight), and thus providing a cooling system arranged to convert that energy into electrical energy by virtue of the transducer is highly advantageous. Where the cooling system is configured for in-flight use, it will be possible to convert energy of the gas flow into electrical energy for the majority of, if not all of, the flight. The gas flow will typically be derived by the aircraft moving through the gas, such as air, typically in a flight condition.

The battery may be comprised in a power supply for a propulsion system of the aircraft. Ensuring that the propulsion system battery is maintained at a suitable temperature is important as energy storage and battery efficiency is dependent on battery temperature. The gas flow path may be defined by a duct extending between the inlet and outlet.

The electrical energy obtained from the transducer may be a function of the battery temperature. That is, a warmer battery may result in, or facilitate, increased energy conversion. This is advantageous as a hotter battery temperature will allow the rate of gas flow to be increased, the gas flow thus having greater kinetic energy as it travels along the gas flow path.

The cooling system may be arranged to monitor the temperature of the battery. The cooling system may be configured to control a mass flow of the gas along the gas flow path as a function of the component temperature. Monitoring the battery temperature is important for battery health. A greater mass flow of gas along the gas flow path will be needed if the battery temperature is greater than desired or required. Additionally, the cooling system therefore does not require additional valves or flow regulators, which increases simplicity and reduces aircraft weight. Alternatively, additional valves or flow regulators may add additional degrees of control, or redundancy.

The transducer may be a turbine. The turbine may be provided in the gas flow path. The turbine may be arranged to be rotated by the flow of gas. A turbine is advantageously suited for capturing the kinetic energy of the gas flow. The mass flow may be a function of the rotational speed of the turbine. This is advantageous as battery cooling is related to turbine speed. The turbine may be downstream of the battery. This advantageously encourages flow along the gas flow path and over the battery, and at the same time is a good position for recovering energy from the gas.

The turbine may be comprised in a wheel of the aircraft. The turbine may be comprised in a wheel hub. A wheel hub may comprise vanes. Advantageously, a separate turbine need not be provided. The wheel hub may spin separately to the wheel. Vanes assist in capturing the kinetic energy of the gas flow.

A part of the aircraft wheel may be exposed from the belly fairing such that during flight, the wheel is rotated by ambient airflow past the wheel. This encourages airflow along the airflow path, thus cooling the battery.

The cooling system may be arranged to direct the electrical energy from the transducer to the battery or to a propulsion system of the aircraft. Advantageously, the recovered energy can therefore be stored for later use, or used to propel the aircraft. In another example, there may be no battery charging, and the system can simply be employed to cool the battery, and in a controlled manner. Alternatively, the cooled battery and the charging battery may not be the same. One battery may be cooled, and another (different) battery may be charged.

The propulsion system may comprise a ground propulsion system arranged to drive one or more wheels of the aircraft. The transducer may be comprised in the one or more wheels.

According to a seventeenth aspect of the present invention there is provided an aircraft comprising a cooling system according to the sixteenth aspect of the present invention.

The aircraft may comprise body-mounted landing gear. Alternatively, the aircraft may comprise landing gear provided on struts extending from beneath the aircraft wings or nacelles.

According to an eighteenth aspect of the present invention there is provided a method of cooling a battery in an aircraft using a flow of gas, the method comprising the steps of:

a. directing a flow of gas proximal to the battery to cool the battery; and

b. converting energy of the gas flow into electrical energy using a transducer.

Although some exemplary embodiments of the present invention are shown and described, it will be appreciated by those skilled in the art that various changes and modifications might be made without departing from the scope of the invention, as defined in the appended claims.

Additionally, it will be appreciated that the various aspects and embodiments are closely related in terms of concept and technical implementation, and as a result various features of those aspects and embodiments are clearly combinable with one another, and/or may replace one another, unless such combination or replacement would be understood by the skilled person reading this disclosure to be mutually exclusive.

BRIEF DESCRIPTION OF THE DRAWINGS

For a better understanding of the invention, and to show how embodiments of the same may be carried into effect, reference will now be made, by way of example only, to the accompanying diagrammatic drawings in which:

Figure 1 shows an aircraft according to an embodiment of the present invention;

Figure 2 shows a general propulsion management system according to an embodiment of the present invention;

Figure 3 shows general methodology associated with a propulsion management system according to an embodiment of the present invention;

Figure 4 shows a graph of total instantaneous power supplied by the aircraft propulsion system versus time during a takeoff roll according to an embodiment of the present invention;

Figure 5 shows a graph of aggregate power during a takeoff roll for each of an aircraft comprising both a ground propulsion system and an air propulsion system according to an embodiment of the present invention, and an aircraft comprising only an air propulsion system;

Figure 6 shows a graph of speed versus time during a takeoff roll for each of an aircraft comprising both a ground propulsion system and an air propulsion system according to an embodiment of the present invention, and an aircraft comprising only an air propulsion system;

Figure 7 shows a takeoff trajectory for each of an aircraft comprising both a ground propulsion system and an air propulsion system according to an embodiment of the present invention, and an aircraft comprising only an air propulsion system;

Figure 8 shows a propulsion management system according to an embodiment of the present invention;

Figure 9 shows an alternative block diagram of the propulsion management system architecture.

Figure 10 shows a graph of thrust versus speed for an aircraft comprising both ground and air propulsion systems according to an embodiment of the present invention; and

Figure 11 shows a general propulsion management system according to an embodiment of the present invention;

Figure 12 shows general methodology associated with a propulsion management system according to an embodiment of the present invention;

Figure 13 shows plots of propeller advance ratio versus propeller efficiency;

Figure 14 shows an energy recovery system provided in the aircraft according to an embodiment of the present invention;

Figure 15 shows a general energy recovery system according to an embodiment of the present invention;

Figure 16 shows general methodology associated with an energy recovery system according to an embodiment of the present invention;

Figure 17 shows a general energy recovery system according to an embodiment of the present invention;

Figure 18 shows general methodology associated with an energy recovery system according to an embodiment of the present invention;

Figure 19 shows a general propulsion management system according to an embodiment of the present invention;

Figure 20 shows general methodology associated with a propulsion management system according to an embodiment of the present invention;

Figure 21 shows a cooling system for cooling the battery of the aircraft propulsion system according to an embodiment of the present invention;

Figure 22 shows a general cooling system according to an embodiment of the present invention; and

Figure 23 shows general methodology associated with a cooling system according to an embodiment of the present invention.

DETAILED DESCRIPTION

Referring to Figure 1, an aircraft 1 is provided with landing gear comprising wheels 2. The aircraft comprises a propulsion system comprising a ground propulsion system 4 and an air propulsion system 6. The ground propulsion system 4 comprises ground propulsion system motors 8 arranged to drive the wheels 2. The air propulsion system 6 comprises propellers 10 and air propulsion system motors 12 arranged to drive the propellers 10. The ground propulsion system 4 and air propulsion system 6 share a power supply 3 comprising an energy accumulator, which in this exemplary embodiment, comprises a battery 14. The battery 14 is configured to supply power to the ground propulsion system motors 8 and to the air propulsion system motors 12.

In this exemplary embodiment, the aircraft 1 comprises body-mounted landing gear. Nevertheless, it will be appreciated by the person skilled in the art that alternative landing gear arrangements may also be employed. For example, the landing gear may be located on struts which extend from beneath the aircraft wings or nacelles.

Additionally, in this exemplary embodiment the air propulsion system 6 comprises four propellers 10. Nevertheless, it will be appreciated by the person skilled in the art that the air propulsion system 6 may comprise any suitable number of propellers 10 and associated air propulsion system motors 12. For example, the air propulsion system may comprise two, four or six propellers 10.

In an exemplary embodiment, the power supply 3 further comprises an internal combustion engine 16 drivingly connected to the propellers 10. Whilst primarily provided as a backup power source, the internal combustion engine 16 can assist the propulsion system when high accelerations are demanded, or when battery recharging is preferable.

In another embodiment, depending on specific implementations of the invention, the ground propulsion system may be driven by a combustion engine, and/or the air propulsion system may be driven by a combustion engine. As discussed below, however, at least partial electrical implementation may be advantageous.

Referring back to Figure 1, a propulsion management system 20 is arranged to control the ground and air propulsion systems 4, 6. As will be described in greater detail herein, the propulsion management system 20 is arranged to control the ground propulsion system 4 to drive the wheels 2 during a takeoff roll.

In a taxiing phase, the aircraft 1 is positioned on the runway ready for takeoff. The propulsion management system 20 is then employed for a takeoff roll. When thrust is demanded by the aircraft pilot, the propulsion management system 20 controls the ground propulsion system 4 to drive the wheels 2 by supplying power from the battery 14 to the ground propulsion system motors 10. The aircraft 1 is thus caused to accelerate for a first time period using the ground propulsion system 4 to increase the aircraft speed as it travels along the runway.

Once a predetermined or desired speed is achieved by operation of the ground propulsion system 4, the propulsion management system 20 then controls the air propulsion system 6 to drive the propellers 10 by causing a supply of power to be directed from the battery 14 to the air propulsion system motors 12. The aircraft 1 is thus caused to accelerate for a second time period using the air propulsion system 6 to continue to increase the aircraft speed up to, and optionally above, an appropriate takeoff speed. The transition from ground propulsion drive to air propulsion drive is automatic and is handled by the system 20, that is, it does not require any particular or dedicated input from the pilot.

Overlap between the aforementioned first and second time periods can be controlled to cause the aircraft 1 to perform a desired takeoff roll. For example, in one exemplary use of the propulsion management system 20, the system 20 causes the ground propulsion system 4 and the air propulsion system 6 to operate with no overlap in operational periods. This smooths out acceleration of the aircraft. In another exemplary use of the propulsion management system, the system causes the ground propulsion system 4 and the air propulsion system 6 to operate with an overlap so as to accelerate the aircraft at a faster rate. It is envisaged that the overlap could be the majority of, or all of, a takeoff roll, which may be particularly advantageous where rapid acceleration is required, for example where the aircraft is to perform a takeoff roll on a short runway.

In Figure 2, a general propulsion management system according to an embodiment of the present invention is shown. The propulsion management system 20 is for an aircraft 1 comprising one or more wheels 2, and a ground propulsion system 4 arranged to drive one or more wheels 2 of the aircraft 1. The propulsion management system 20 is arranged to control the ground propulsion system 4 to drive one or more wheels 2 of the aircraft 1 during a takeoff roll, the takeoff roll being subsequent to a taxiing phase.

In Figure 3, general methodology principles associated with a propulsion management system according to an embodiment of the present invention are shown. Step 100 comprises providing an aircraft 1 comprising one or more wheels 2 and a ground propulsion system 4 arranged to drive one or more wheels 2 of the aircraft 1. Step 102 comprises controlling the ground propulsion system 4 to drive the one or more wheels 2 of the aircraft 1 during a takeoff roll, the takeoff roll being subsequent to a taxiing phase.

Figure 4 shows a graph of total instantaneous power “TIP” supplied by both the ground and air propulsion systems versus time “t” during a takeoff roll. The ground propulsion system 4 is operational for a first time period 104. The air propulsion system 6 is operational for a second time period 106. As shown in the figure, there is an overlap period 108 between the operational periods, which is advantageous in providing rapid acceleration, and/or a seamless transition between periods, which may offer flexibility in technical implementation or provide an improved user (e.g. passenger) experience.

A further advantage of the invention is succinctly shown in Figure 4. The ground propulsion system 4 is more efficient than the air propulsion system 6 at low speeds. The ground propulsion system 4 therefore requires less power to accelerate the aircraft from standstill, as is shown by the lower-level power line during the first time period 104. Once the pre-determined speed is achieved, the propulsion management system 20 causes a transition to the air propulsion system 6, and the air propulsion system 6 is operational for the second time period 106at a constant power level. The shaded area 110 indicates the power that would have been required had the air propulsion system 6 been operational for the entire takeoff roll, and thus indicates the power saved by using providing the propulsion management system 20 to control the ground propulsion system 4 to initially accelerate the aircraft.

Figure 5 shows aggregate power “AP” versus time “t” during a takeoff roll for an aircraft 1 having both ground and air propulsion systems 4, 6 (labelled 120), and an aircraft having only an air propulsion system (labelled 122). It has been found that the aggregate power required during a takeoff roll is lower when the ground propulsion system 4 is initially used to accelerate the aircraft 1 before transitioning to the air propulsion system 6, when compared with initiating the takeoff roll using only the air propulsion system 6. Such a system, according to embodiments of the invention, leads to a reduction in aggregate power of 20% for the same takeoff distance in at least one example. The same or better savings may be achieved, depending on how much use is made of the ground propulsion system, balanced against acceleration that might be too great for comfort of passengers or users.

Figure 6 shows speed “v” of an aircraft 1 having both ground and air propulsion systems 4, 6 (labelled 130), and an aircraft having only an air propulsion system (labelled 132) versus time “t”. The shaded region 134 indicates the range of possible aircraft lift-off speeds. The Figure shows that, in addition to the lower aggregate power, it is possible to achieve lift-off speed sooner using a system according to example embodiments This can lead to a 12.5% reduction in the distance travelled from the start of the takeoff roll to take off, in this example alone. This is advantageous where the aircraft is to take off from a short runway, and also in reducing noise pollution as the aircraft climbs to altitude sooner. The same or better savings may be achieved, depending on how much use is made of the ground propulsion system, balanced against acceleration that might be too great for comfort of passengers or users.

Figure 7 shows a graph of altitude “A” versus distance from start of the takeoff roll “d” and illustrates how operation of the ground propulsion system 4 can be advantageous in reducing noise pollution. In the field, noise pollution measurements are obtained by measuring the noise level at the ground, a fixed distance from the start of the takeoff roll. The reduction in takeoff distance facilitated by the propulsion management system 20 arranged to control the ground propulsion system 4 and the air propulsion system 6 allows the aircraft 1 to begin climbing to altitude sooner (as indicated by line 140) compared with an aircraft 1 having only an air propulsion system 6 (as indicated by line 142). The noise levels measured at a point 144 on the ground from the aircraft 1 following the solid line trajectory are therefore lower. This noise level might be reduced further, if any propellers of the air propulsion system are optimised for the climb phase, as opposed to needing to be optimised for the takeoff roll. The invention facilitates this optimisation, since the ground propulsion system means that the air propulsion system is not needed for the entire (and certainly initial period of) the takeoff roll.

Referring now to Figure 8, a ground propulsion system motor 8 is drivingly connected to each aircraft wheel 2. As a result, the ground propulsion system motors 8 can drive the aircraft wheels independently. A sensor assembly 22 is arranged in use to measure one or more of the wind speed, wheel speeds, travel path and trajectory of the aircraft (e.g. one or more situational properties) and the propulsion management system 20 is arranged to monitor the sensor assembly 22. Crosswinds can cause an aircraft to deviate from a desired takeoff travel path, or be urged towards such a deviation. If the sensor assembly 22 senses such deviation or urging during a takeoff roll, the propulsion management system 20 responds by causing the ground propulsion system to drive the wheels 2 at different speeds, by increasing or decreasing the motor torque as required, so as to return the aircraft 1 to the desired travel path.

Aircraft are often required to take off in, or following, adverse weather conditions. Snow, ice or standing water presents a considerable risk during a takeoff roll and will affect wheel traction. If during a takeoff roll the propulsion management system 20 monitoring the sensor assembly 22 detects a deviation in rotational speed of each the aircraft wheels 2, the propulsion management system 20 responds to apportion drive to the wheels 2 accordingly. For example, when the propulsion management system 20 becomes aware of a wheel having a rotational speed greater than the rotational speed of the other aircraft wheels by a threshold amount (e.g. a slip condition, or a condition where the drive is causing the aircraft to turn unintentionally through the wheel driving), the propulsion management system responds by causing the ground propulsion system 4 to reduce the torque provided to the faster rotating wheel, or perhaps increasing the torque to the slower rotating wheel. The former is more likely, as in the control of automobiles, to prevent or reduce wheelspin. Such a system operates in conjunction with the above described sensor assembly 22 for measuring the aircraft travel path. The propulsion management system 20 can thus vary the torque provided to the wheels 2 in dependence on both the travel path and the rotational speed of the wheels, to ensure that the aircraft remains on the desired takeoff travel path.

Referring back to Figure 8, the propulsion management system 20 is arranged to apportion power from the power supply 3 between the ground propulsion system 4 and the air propulsion system 6. The propulsion management system 20 does so based on input from a single thrust actuator (e.g. lever) 50, as in a conventional aircraft, and apportions power based on the level of actuation of the lever 50. Or, if an aircraft has one lever for each air propulsion engine, the invention envisages that same level being used for any one or more associated ground propulsion drivers. As a result, the pilot does not have to control the power apportionment manually, or at all. The apportionment is in the background and automatic. Additionally, the propulsion management system can be retrofitted to existing aircraft, and the cockpit layout need not be altered or adjusted to accommodate the propulsion management system 20. This system when employed during a takeoff roll is highly advantageous as the pilot may focus on other tasks than energy apportionment.

The propulsion management system 20 comprises a processor 23, a memory 25, a communications unit 27 and a user interface 29. The user interface 29 allows information to be provided to the propulsion management system 20 and also allows information relating to the aircraft systems to be accessed by the user. Information can also be uploaded to the propulsion management system 20 via the communications unit 27. The propulsion management system 20 is configured to process and store flight plan information, which may be data relating to a past, present or future flight, in memory.

Figure 9 shows an alternative block diagram of the propulsion management system architecture. The propulsion management system 20 communicates with an operational information unit 62 to access flight information, including flight plans. The propulsion management system communicates with a power information unit 64 to access information relating to the status of a power supply, which includes the battery 14 and the internal combustion engine 16. The propulsion management system 20 is arranged to control the operation of the internal combustion engine 16. The propulsion management system 20 is also arranged to communicate with a flight control computer (FCC) 66, which communicate with a power management and distribution unit 68. The propulsion management system 20 is arranged to output information to a user interface 70.

As mentioned above, the propulsion management system 20 receives information from the power supply 3. Such information includes the energy potential of the power supply 3, which informs the pilot of the battery charge level and, where the aircraft comprises an internal combustion engine 16, the fuel level. On receiving this information, the propulsion management system controls the apportionment of power between the ground propulsion system 4 and the air propulsion system 6, and controls the supply of power from each power source, taking into account flight information such as:

a. Acceleration profiles stored in memory which result in: the quietest possible takeoff, the shortest possible takeoff, minimum power usage for takeoff, the smoothest possible acceleration, suitable levels of torque being applied to the wheels to ensure traction with the runway surface is maintained;

b. Deceleration profiles stored in memory which result in: the quietest possible landing, the shortest possible landing, minimum power usage to slow the aircraft, the smoothest possible deceleration, suitable levels of torque being applied to the wheels to ensure traction with the runway surface is maintained;

c. Power source management requirements, including: preserving battery charge, using excess charge to make capacity for regeneration (including decelerating the aircraft using the energy recovery systems described in detail below), using excess fuel, battery temperature;

d. Flight plan information, including: the distance to the destination, time to destination, turnaround time at destination;

e. Airport data, including: runway length at takeoff airport or at destination airport, availability of charging ports at destination; or

f. Situational conditions, including: wind speed, wheel speed, travel path and trajectory of the aircraft.

Examples of the propulsion management system 20 controlling energy apportionment include:

a. where the quietest possible takeoff is required, the propulsion management system prioritises the supply of power to the ground propulsion system for as long as possible, and without apportioning power to the air propulsion system until necessary;

b. where the shortest possible takeoff is required, the propulsion management system apportions power between the ground and air propulsion systems to produce maximum acceleration, in particular supplying maximum power to both systems;

c. where minimum power usage is required, the propulsion management system apportions between the ground and air propulsion system to produce the most efficient takeoff roll;

d. where smooth acceleration is required, the propulsion management system selects an appropriate acceleration profile, apportions power and controls the overlap between operation of the ground and air propulsion management system so that acceleration remains substantially constant throughout the takeoff roll;

e. where maximum deceleration, or smooth deceleration, is required, the propulsion management system may control operation of the energy recovery systems described in detail below, apportioning power to the energy recovery systems in addition or instead of to the propulsion systems;

f. where it is desirable to preserve battery charge, the propulsion management system causes power to be supplied from the internal combustion engine for the remainder of the flight, or until battery charge is restored or increased by operating one of the recovery systems or cooling system as described in detail below; and

g. where it is desirable to minimise turnaround time at the destination, the propulsion management system apportions power to the air propulsion system during a landing roll to provide reverse thrust, and does not apportion power to the energy recovery system interacting with the wheels as described in detail below so as to minimise heating of the aircraft wheels.

The propulsion management system 20 may do any or all of the above with reference to information stored in memory in relation to previous flights.

Figure 10 shows a graph of net thrust “T”, produced by energy apportionment, versus speed “v” for an aircraft comprising both ground and air propulsion systems. The upper region 300shows the thrust available from the ground propulsion system 4. The lower region 302 shows the thrust available from the air propulsion system 6. The dashed line 304 shows the net thrust possible whilst adhering to airport noise restrictions. The propulsion management system operates to apportion energy between the ground propulsion system 4 and the air propulsion system 6 so as to adhere to the noise restriction.

In Figure 11, a general propulsion management system according to an embodiment of the present invention is shown. The propulsion management system 20 is for an aircraft 1, the aircraft 1 comprising one or more wheels 2, a power supply 3, a ground propulsion system 4 arranged to drive one or more wheels 2 of the aircraft 1 and an air propulsion system 6. The propulsion management system 20 is arranged to apportion power from the power supply 3 between the ground propulsion system 4 and the air propulsion system 6.

In Figure 12, general methodology principles associated with a propulsion management system according to an embodiment of the present invention are shown. Step 150 comprises providing an aircraft 1 comprising one or more wheels 2, a power supply 3, a ground propulsion system 4 arranged to drive one or more wheels 2 of the aircraft 1, and an air propulsion system 6. Step 152 comprises apportioning power from the power supply 3 between the ground propulsion system 4 and the air propulsion system 6.

Figure 13 shows plots of propeller advance ratio “J” versus propeller efficiency “η”. Advance ratio is the ratio of the aircraft forward speed to the rotational speed of the propellers. The plots illustrate the relationship between advance ratio and propeller efficiency for various propeller pitch angles “β”. Pitch angle is an important consideration in propeller design because of this relationship. At low advance ratio J (that is, in and around the region 220), which is typically at low aircraft forward speeds, the propeller efficiency η is low, and a significant proportion of power supplied to the air propulsion system 6 is wasted as noise.

During a takeoff roll, the propulsion management system 20 causes the aircraft 1 to accelerate using the ground propulsion system 4 and the aircraft forward speed increases. When the propellers 10 are subsequently activated, they are in a region of increased efficiency (that is, in and around the region 222). This means that when the propellers 10 are activated, they produce considerably less noise than if they were operating at low aircraft speed in and around region 220, for example, if the propellers 10 were used to accelerate the aircraft 1 from stationary.

Variable pitch propellers are typically employed to maintain high propeller efficiency across a wide range of propeller advance ratios. This, of course, requires a degree of mechanical and control complexity. Nevertheless, in an exemplary embodiment, the aircraft propellers 10 are fixed pitch propellers. The fixed pitch propellers 10 are optimised for the climb phase of flight. By providing the ground propulsion system, the propeller need not be optimised for low advance ratio, enabling simpler fixed pitch propellers to be provided. Optimising the propellers 10 for the climb phase means that the propeller pitch is set so as to produce minimum noise during climb by operating most efficiently during the range of speeds achieved during the climb phase. This might mean that the propellers, and/or any control systems, may be simpler, cheaper, and even lighter.

Figure 14 shows an energy recovery system 30 provided in the aircraft 1. The energy recovery system 30 is connected to the ground propulsion system motors 10. The energy recovery system 30 causes the electric motors 10 to operate as generators, absorbing or generally using rotational kinetic energy from the aircraft wheels 2 and generating electricity which is fed to the battery 14 where it is stored. This could happen in flight, or on the ground. Advantageously, the energy recovery system 30 is operated to provide braking to the aircraft 1 during a landing roll. By adjusting the load on the motors 10, the energy recovery system 30 controls the rate of deceleration of the aircraft wheels and thus the aircraft. Using the energy recovery system 30 to decelerate the aircraft instead of or alongside friction brakes also reduces the brake temperature, which decreases turnaround time of the aircraft at a destination airfield or airport, since the brakes need less time to return to a safe operating temperature.

In Figure 15, a general energy recovery system according to an embodiment of the present invention is shown. The energy recovery system 30 is for an aircraft. The energy recovery system comprises a transducer assembly 10 arranged to selectively interact with one or more wheels 2 of the aircraft to extract energy from the wheels 2. The energy recovery system 30 further comprises an energy accumulator 3 for storing the extracted energy.

In Figure 16, general methodology principles associated with an energy recovery system according to an embodiment of the present invention are shown. Step 230 comprises interacting a transducer assembly 10 with one or more wheels of the aircraft to extract energy from the wheels. Step 232 comprises storing the extracted energy in an energy accumulator 3.

In this exemplary embodiment, the aircraft is provided with an energy recovery system 30 in conjunction with the propulsion management system 20, and the energy stored in the battery 14 of the energy recovery system is used to power the ground propulsion system 4 during a subsequent takeoff roll. Whilst in this exemplary embodiment Li-Ion batteries are employed, supercapacitors and flywheels are also a feasible alternative energy storage means. Again, this might reduce turnaround time of the aircraft at a destination airfield or airport, since there is no (or a lesser) need to recharge the battery.

The energy recovery system 30 is also connected to the air propulsion system motors 12. The energy recovery system 30 causes the two outermost propeller motors to selectively interact with the propellers to operate as generators, absorbing rotational kinetic energy from the propellers and generating electricity which is fed to the battery 14 where it is stored. This interaction is employed during a descent phase of flight. When the energy recovery system 30 is in interaction with the two outermost propellers, the propulsion management system 20 controls the air propulsion system 6 not to provide drive to those propellers. Instead, the propellers are allowed to rotate freely as they push through the air. The motors variably inhibit motion of the propellers to control the rotational speed of the propellers. By adjusting the load on the motors (e.g. by the generation of electricity), the energy recovery system 30 controls the rate of deceleration of the aircraft 1 by increasing the drag produced by the two peripheral propellers. The ability to increase the drag facilitates a steep angle of aircraft descent. This is highly advantageous in reducing aircraft noise pollution, and possibly allowing more locations to be used as airfields or airports. Adjusting the load on the motors also provides greater or lesser rate of battery charging. Whilst the two outermost propellers are not driven, the innermost two propellers may be driven (perhaps more than usual) so as to maintain a constant air speed.

In Figure 17, a general energy recovery system according to an embodiment of the present invention is shown. The energy recovery system 30 is for an aircraft. The energy recovery system comprises a transducer assembly 12 arranged to selectively interact with one or more propellers 10 of a propulsion system 6 of the aircraft to extract energy from the propellers.

In Figure 18, general methodology principles associated with an energy recovery system according to an embodiment of the present invention are shown. Step 240 comprises interacting a transducer assembly 12 with one or more propellers 10 of a propulsion system 6 of the aircraft. Step 242 comprises extracting energy from the propellers 12.

The propulsion management system 20 is further arranged to control the air propulsion system 6 to drive the propellers 10 in reverse to provide a reverse thrust. This is particularly advantageous in decelerating the aircraft during a landing roll. The propulsion management system comprises an energy recovery system 30 as described above, and the energy recovery system is connected to the wheels 2 to provide braking effort during a landing roll. As a result, energy recovered during the landing roll is directed to the air propulsion system 6 and used to drive the propellers in reverse to provide a reverse thrust. In an exemplary embodiment, the aircraft comprises such a propulsion management system for driving propellers in reverse and variable pitch propellers. The variable pitch propellers can be adjusted on, or prior to, landing to create a maximum reverse thrust when the propellers are operated in reverse.

In Figure 19, a general propulsion management system according to an embodiment of the present invention is shown. The propulsion management system 20 is for an aircraft comprises an air propulsion system 6 having one or more propellers 10. The propulsion management system 20 is arranged to control the air propulsion system 6 to drive the one or more propellers 10 in reverse in order to provide a reverse thrust.

In Figure 20, general methodology principles associated with a propulsion management system 20 according to an embodiment of the present invention are shown. Step 250 comprises operating the propellers in reverse to provide reverse thrust.

Figure 21 shows a cooling system 40 for cooling the battery 14 of the aircraft propulsion system. The cooling system 40 is provided in the belly fairing of the aircraft and comprises an inlet 42, of the type developed by the National Advisory Committee for Aeronautics (NACA), opening into an airflow duct 44 which extends through the belly fairing to a NACA outlet 46. The battery 14 is provided with a battery temperature sensor 16. The battery 14 is located upstream in the airflow duct 44. The airflow duct 44 directs cool air from outside the aircraft across the battery 14 to provide cooling. The battery is located close to a outer mould line 48 of the aircraft 1, and so some external skin conductive cooling also takes place.

The landing gear is mounted in the belly fairing. The landing gear is retractable into the airflow duct 44, downstream of the battery 14. When the landing gear is in a retracted position, a lower portion of each wheel 2 projects through a lower aperture in the duct 44 and out through the outer mould line 48 of the belly fairing. The airflow duct 44 directs the now heated air towards and past the lower portion of each wheel 2 of the landing gear. The airflow duct 44 connects to the outlet 46 downstream of the wheels 2. The outlet 46 is in a location of low pressure relative to the inlet 42 to encourage air flow through the duct 44.

As the lower portion of each wheel 2 projects out through the outer mould line 48 of the belly fairing, in flight airflow around the outside of the aircraft 1 causes the wheels 2 to rotate. Wheel hubs 70 comprise vanes located in or projecting from the side of the wheels to provide an increased surface area for contact with the airflow. The vanes are configured such that the airflow through the airflow duct passing each wheel encourages the wheels to rotate in the same direction as the rotation caused by the outside airflow.

It will be appreciated that 'internal' airflow (that is, not outside airflow) across and past the battery, and to and past the wheels, may alternatively or additionally cause the wheels to rotate in this way. That is, the wheels need not extend outside of the mould line.

The rotating wheels 2 create suction through the duct 44, which draws air through the duct 44 at a greater rate. The rate of airflow through the airflow duct 44 is thus a function of the rotational velocity of the wheels 2. By increasing the rate of airflow, the battery 14 can be cooled more rapidly, and by decreasing the rate of airflow, the battery 14 can be cooled less rapidly, the temperature maintained, or the battery allowed to heat. The rotational velocity of the wheels is controlled by connecting the cooling system to an energy recovery system of the kind as described above, where energy can be extracted from wheel rotation.

The temperature of the battery is monitored, and an appropriate load is placed on the motors 8 to increase or decrease the rotational velocity of the wheels, to thereby increase or decrease the rate of airflow through the duct 44 as necessary or desired. The configuration of the cooling system 40 is such that a greater motor load produces an increased rate of battery charging and a reduced motor load produces a reduced rate of battery charging.

In Figure 22, a general cooling system according to an embodiment of the present invention is shown. The cooling system 40 is for cooling a battery in an aircraft using a flow of gas. The cooling system comprises an inlet 42, an outlet 46, a gas flow path 44 extending between the inlet 42 and outlet 46, and at least proximal to the battery 14 to cool the battery 14. A transducer 8 is provided in the flow path 44, the transducer 8 being arranged to convert energy of the gas flow into electrical energy.

In Figure 23, general methodology principles associated with a cooling system according to an embodiment of the present invention are shown. Step 260 comprises directing a flow of gas proximal to a battery to cool the battery 14. Step 262 comprises converting energy of the gas flow into electrical energy using a transducer 8.

In addition to, and alongside, the ground and air propulsion systems 4, 6, the propulsion management system 20 is also configured to control the cooling system 40 and energy recovery system 30.

In summary, we provide systems that enable reduction in aircraft noise pollution during the various phases of aircraft flight, including enabling quieter operation during a takeoff roll and a steeper and earlier climb to altitude. We also provide systems which enable quieter and steeper aircraft descent, which are also advantageous in reducing noise pollution. The systems incorporate batteries as a source of power, and thus can be charged using renewable sources, thereby enabling inflight regeneration whilst reducing emissions and carbon footprint. Reduced turnaround time is facilitated as a result of inflight battery charging and by providing a system for reverse thrusting, reducing reliance on wheel braking. Finally, the systems can be provided in new aircraft or can be retrofitted in existing aircraft to provide improved performance during the various stages of aircraft flight.

At least some of the example embodiments described herein may be constructed, partially or wholly, using dedicated special-purpose hardware. Terms such as 'component', 'module' or 'unit' used herein may include, but are not limited to, a hardware device, such as circuitry in the form of discrete or integrated components, a Field Programmable Gate Array (FPGA) or Application Specific Integrated Circuit (ASIC), which performs certain tasks or provides the associated functionality. In some embodiments, the described elements may be configured to reside on a tangible, persistent, addressable storage medium and may be configured to execute on one or more processors. These functional elements may in some embodiments include, by way of example, components, such as software components, object-oriented software components, class components and task components, processes, functions, attributes, procedures, subroutines, segments of program code, drivers, firmware, microcode, circuitry, data, databases, data structures, tables, arrays, and variables. Although the example embodiments have been described with reference to the components, modules and units discussed herein, such functional elements may be combined into fewer elements or separated into additional elements. Various combinations of optional features have been described herein, and it will be appreciated that described features may be combined in any suitable combination. In particular, the features of any one example embodiment may be combined with features of any other embodiment, as appropriate, except where such combinations are mutually exclusive. Throughout this specification, the term "comprising" or "comprises" means including the component(s) specified but not to the exclusion of the presence of others.

Attention is directed to all papers and documents which are filed concurrently with or previous to this specification in connection with this application and which are open to public inspection with this specification, and the contents of all such papers and documents are incorporated herein by reference.

All of the features disclosed in this specification (including any accompanying claims, abstract and drawings), and/or all of the steps of any method or process so disclosed, may be combined in any combination, except combinations where at least some of such features and/or steps are mutually exclusive.

Each feature disclosed in this specification (including any accompanying claims, abstract and drawings) may be replaced by alternative features serving the same, equivalent or similar purpose, unless expressly stated otherwise. Thus, unless expressly stated otherwise, each feature disclosed is one example only of a generic series of equivalent or similar features.

The invention is not restricted to the details of the foregoing embodiment(s). The invention extends to any novel one, or any novel combination, of the features disclosed in this specification (including any accompanying claims, abstract and drawings), or to any novel one, or any novel combination, of the steps of any method or process so disclosed. The invention and above-described features, elements and systems may be adopted or deployed in other transportation and vehicular systems, aerial or otherwise, such as in manned or unmanned drones.

CLAIMS

1. An energy recovery system for an aircraft, the energy recovery system comprising: a transducer assembly arranged to selectively interact with one or more wheels of the aircraft to extract energy from the wheels; and an energy accumulator for storing the extracted energy.

2. An energy recovery system as claimed in claim 1 wherein the transducer assembly is arranged to convert energy from the wheels into electrical energy.

3. An energy recovery system as claimed in claim 2 wherein the transducer assembly is arranged to convert rotational kinetic energy into electrical energy.

4. An energy recovery system as claimed in any preceding claim wherein the energy recovery system is operated during a landing roll.

5. An energy recovery system as claimed in any preceding claim wherein the energy recovery system is operated to provide braking effort during a landing roll.

6. An energy recovery system as claimed in any preceding claim wherein the energy accumulator comprises a battery.

7. An energy recovery system as claimed in any preceding claim wherein the energy accumulator is comprised in a power supply for a propulsion system of the aircraft.

8. An energy recovery system as claimed in claim 7 wherein the propulsion system comprises a ground propulsion system arranged to drive one or more wheels of the aircraft.

9. An energy recovery system as claimed in any preceding claim wherein the transducer assembly comprises one or more electric motors.

10. An energy recovery system as claimed in claim 9 wherein the one or more motors are arranged to drive the one or more wheels of the aircraft, and the electric motor is operated in reverse during operation of the energy recovery system.

11. An energy recovery system as claimed in any preceding claim wherein the transducer assembly is selectively engageable with the one or more wheels.

12. An energy recovery system as claimed in claim 10 wherein the transducer assembly is engaged during a landing roll.

13. An aircraft comprising an energy recovery system as claimed in any preceding claim.

14. A method of energy recovery in an aircraft, the method comprising the steps of:

a) interacting a transducer assembly with one or more wheels of the aircraft to extract energy from the wheels; and

b) storing the extracted energy in an energy accumulator.

15. A method as claimed in claim 14 wherein the transducer assembly converts energy from the wheels into electrical energy.

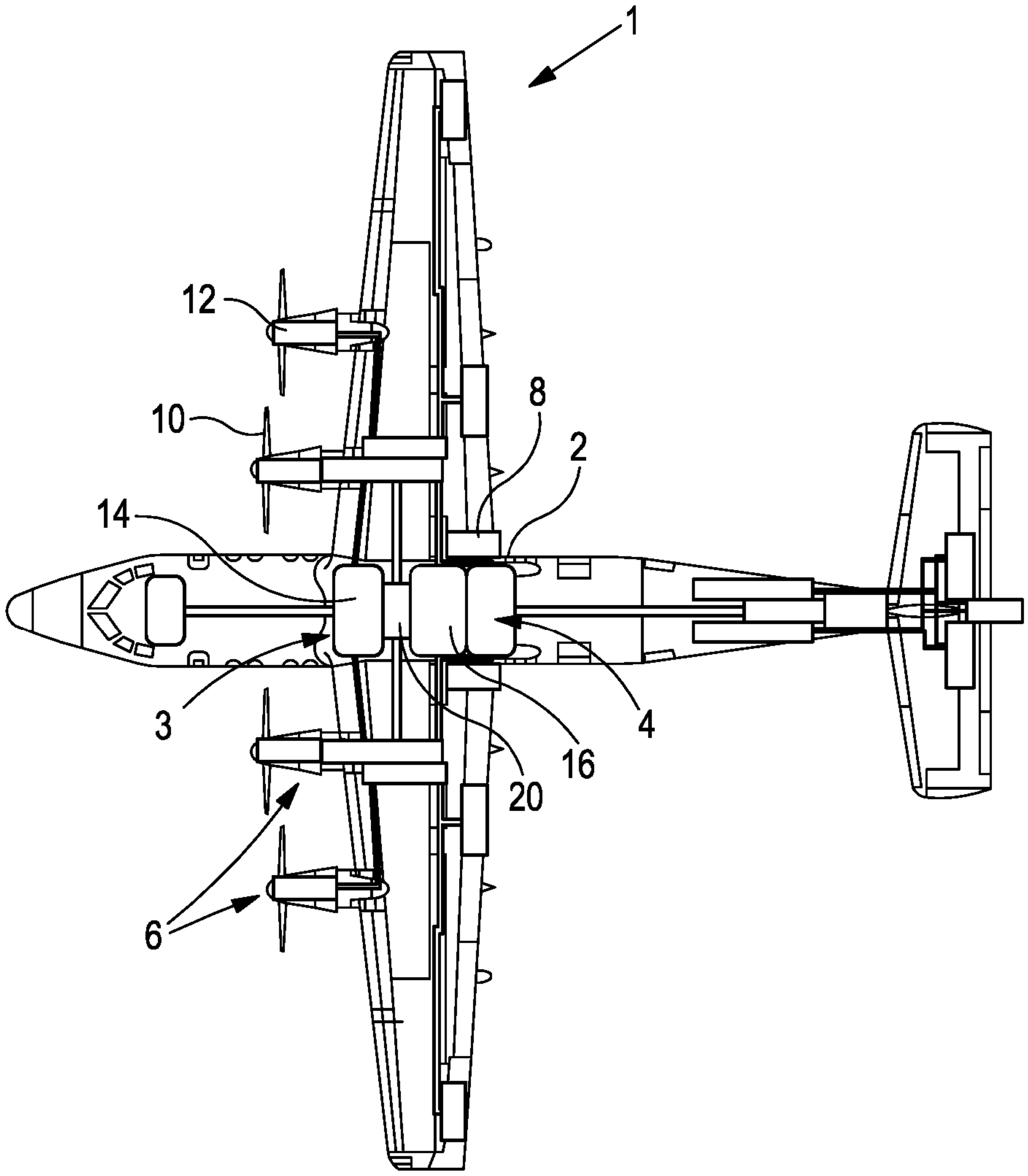

FIG. 1

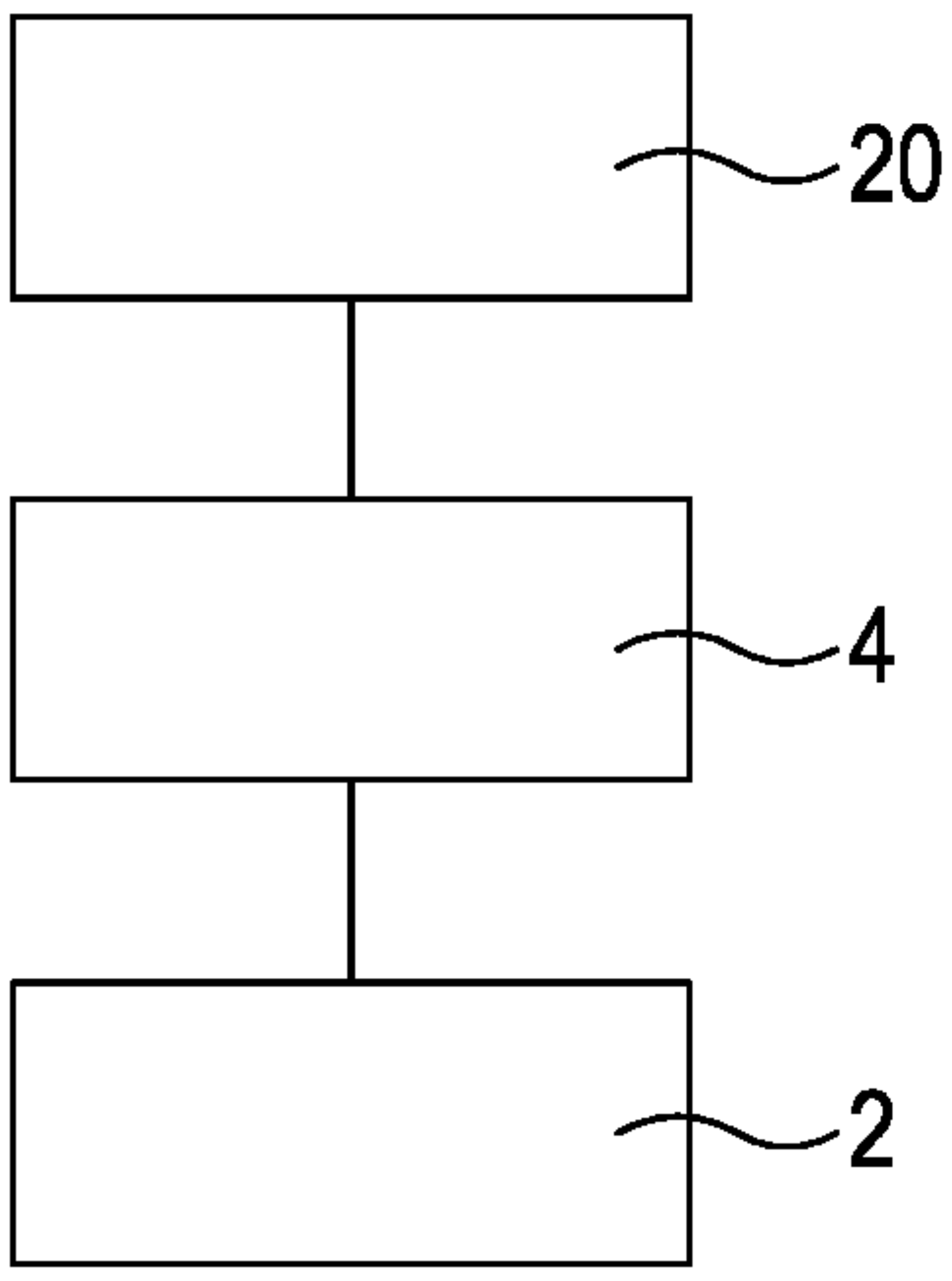

FIG. 2

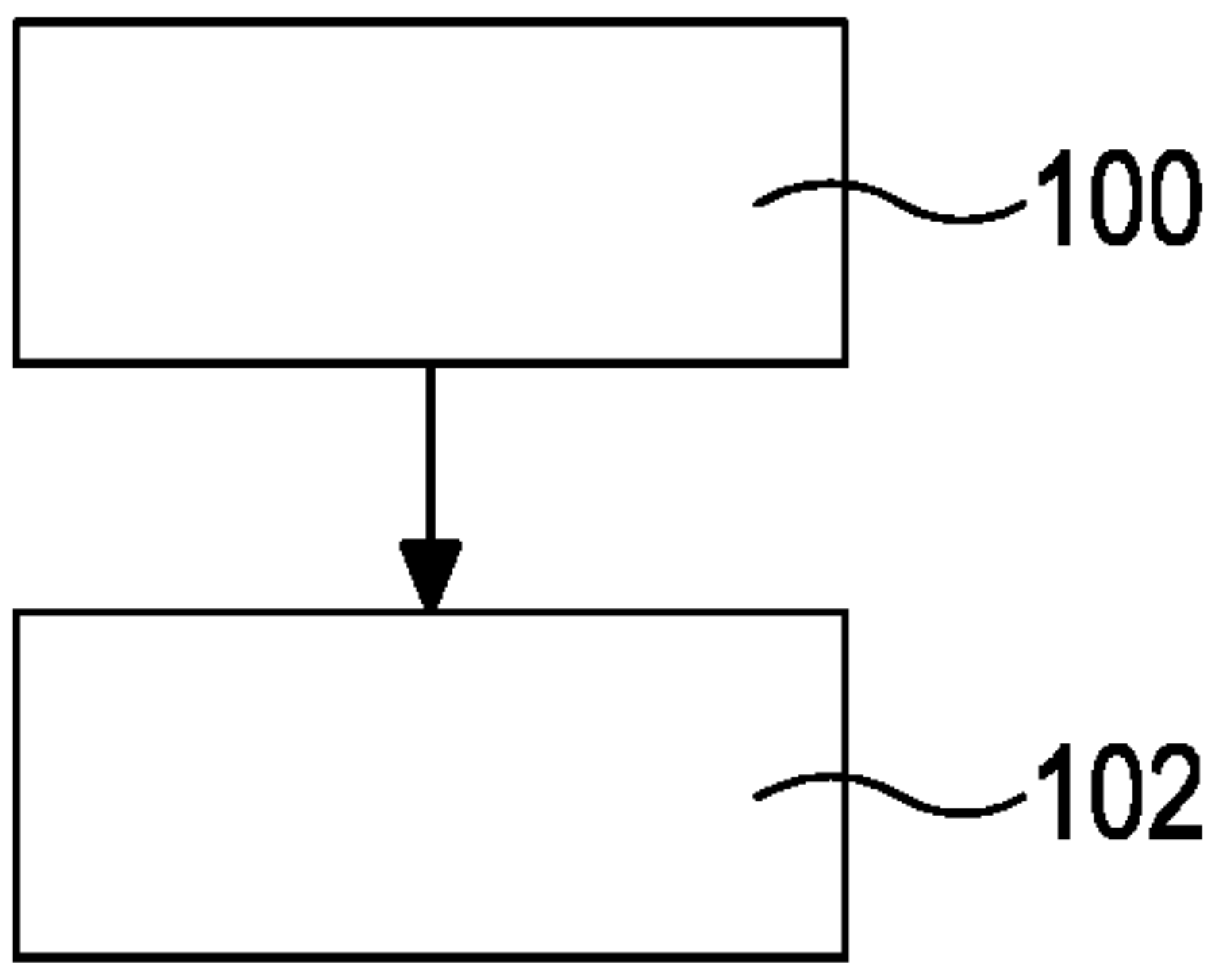

FIG. 3

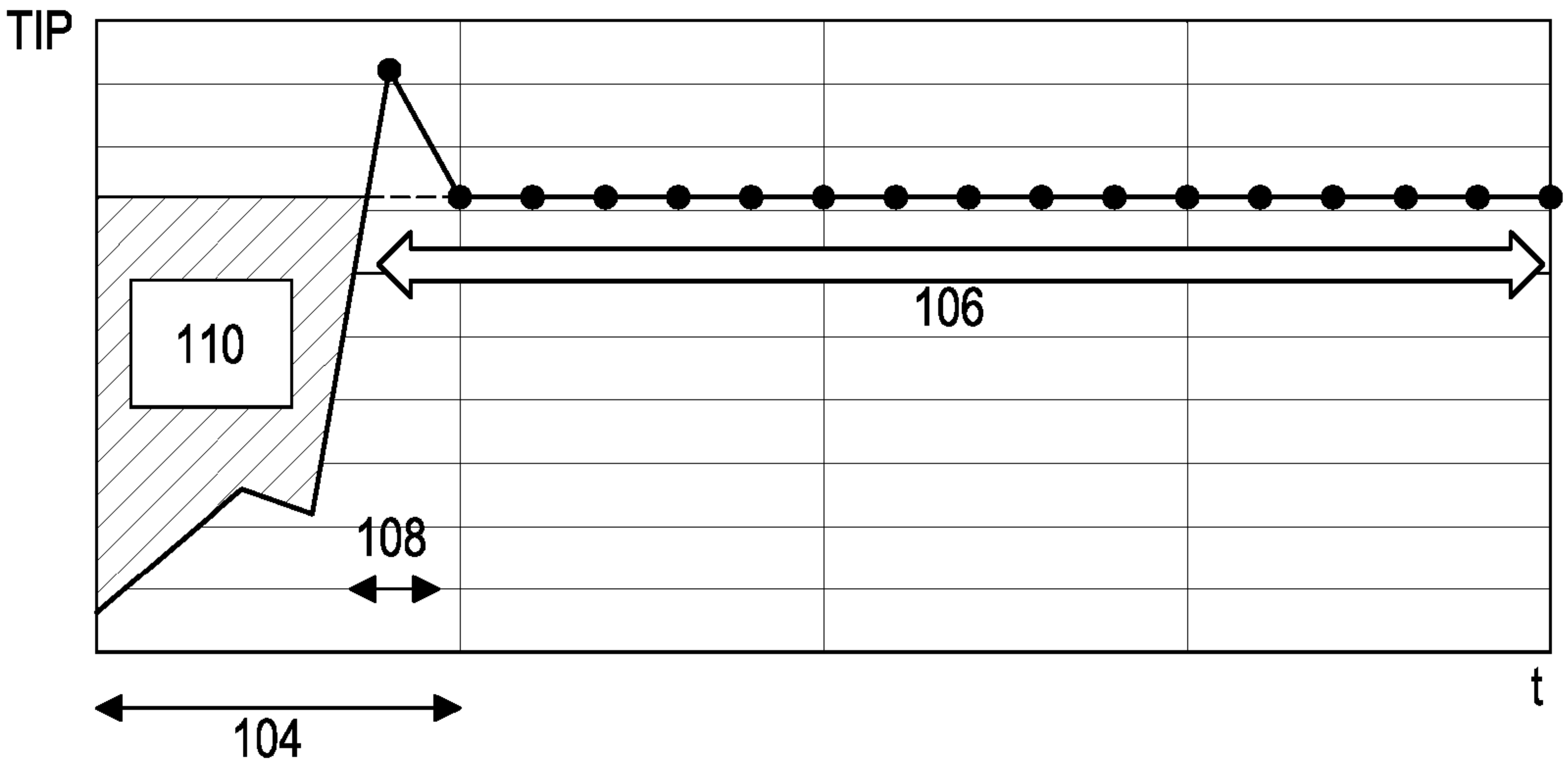

FIG. 4

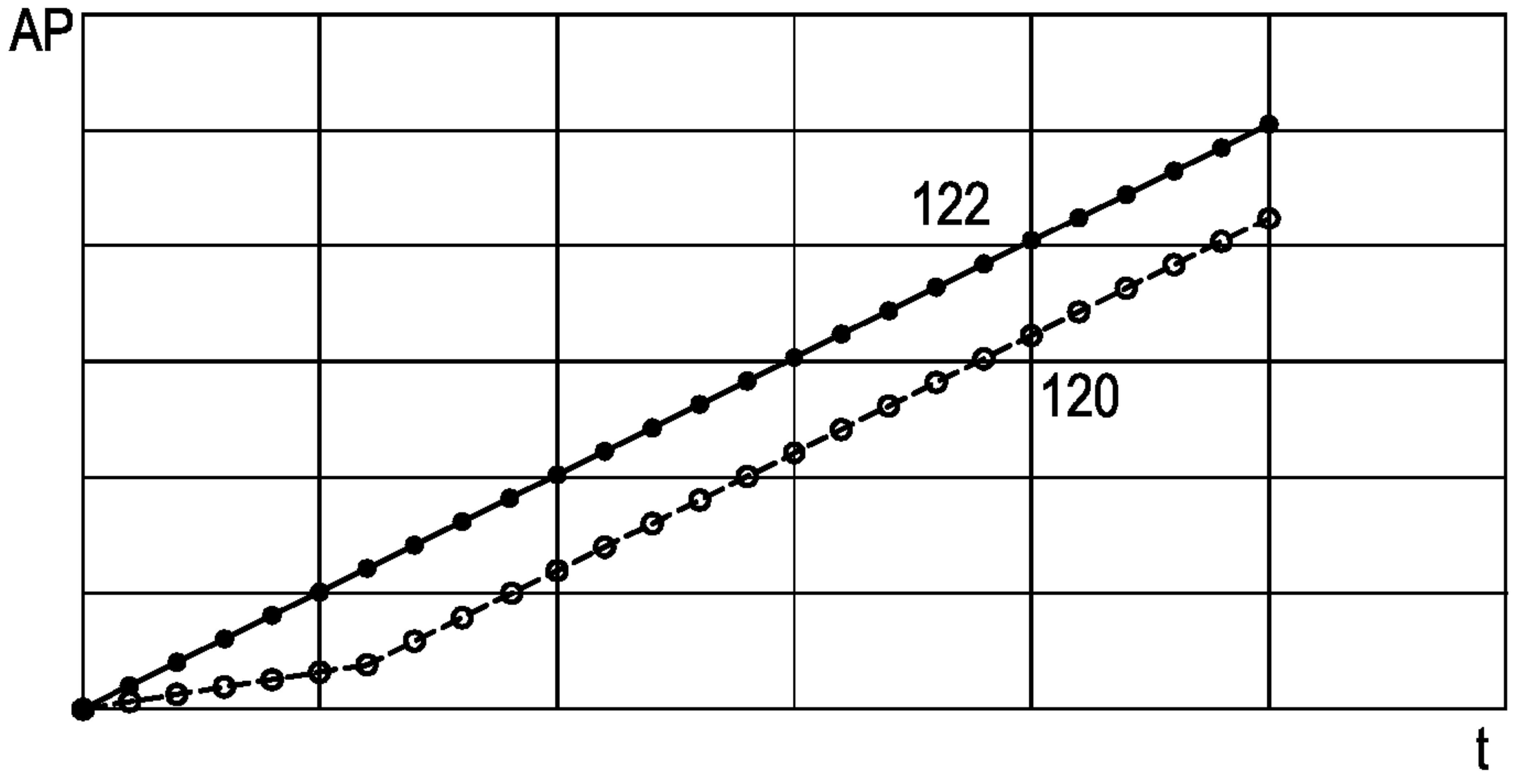

FIG. 5

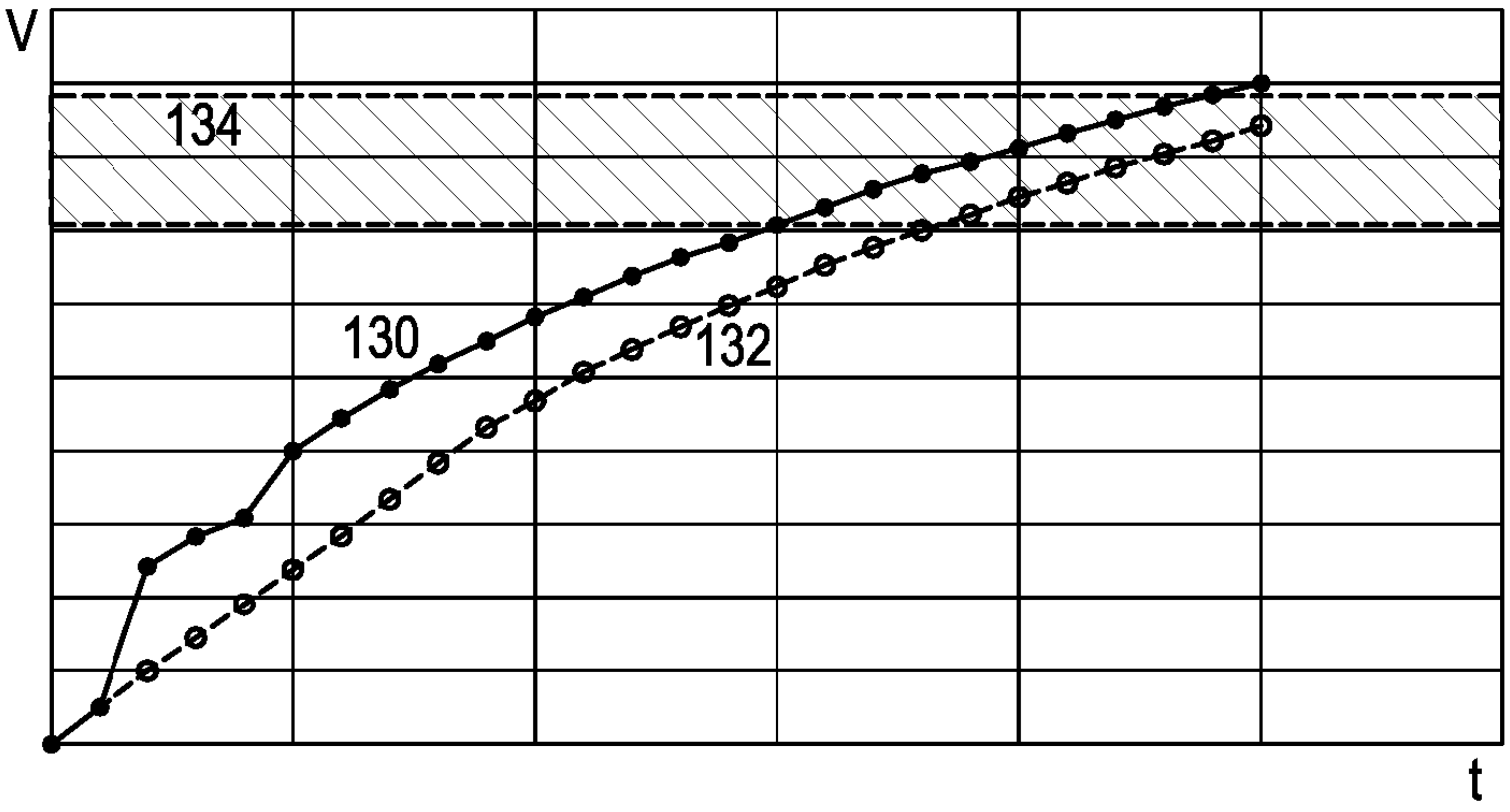

FIG. 6

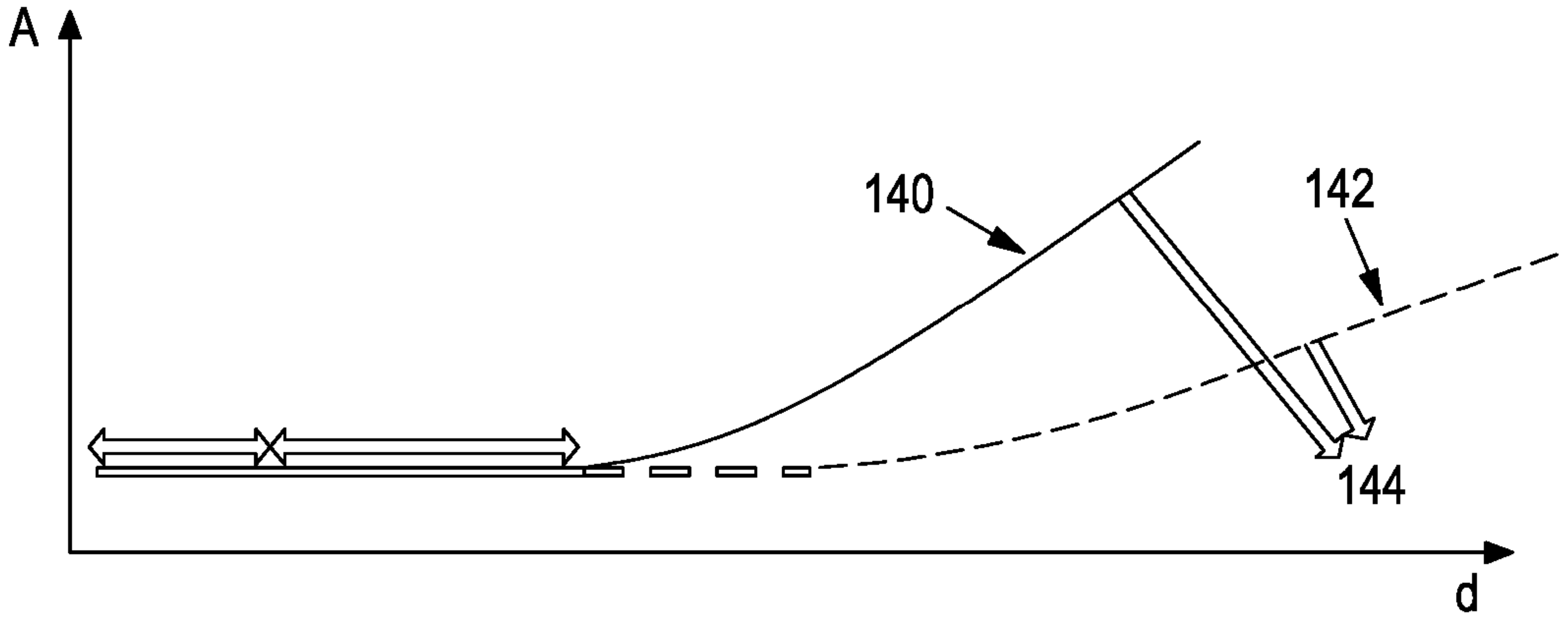

FIG. 7

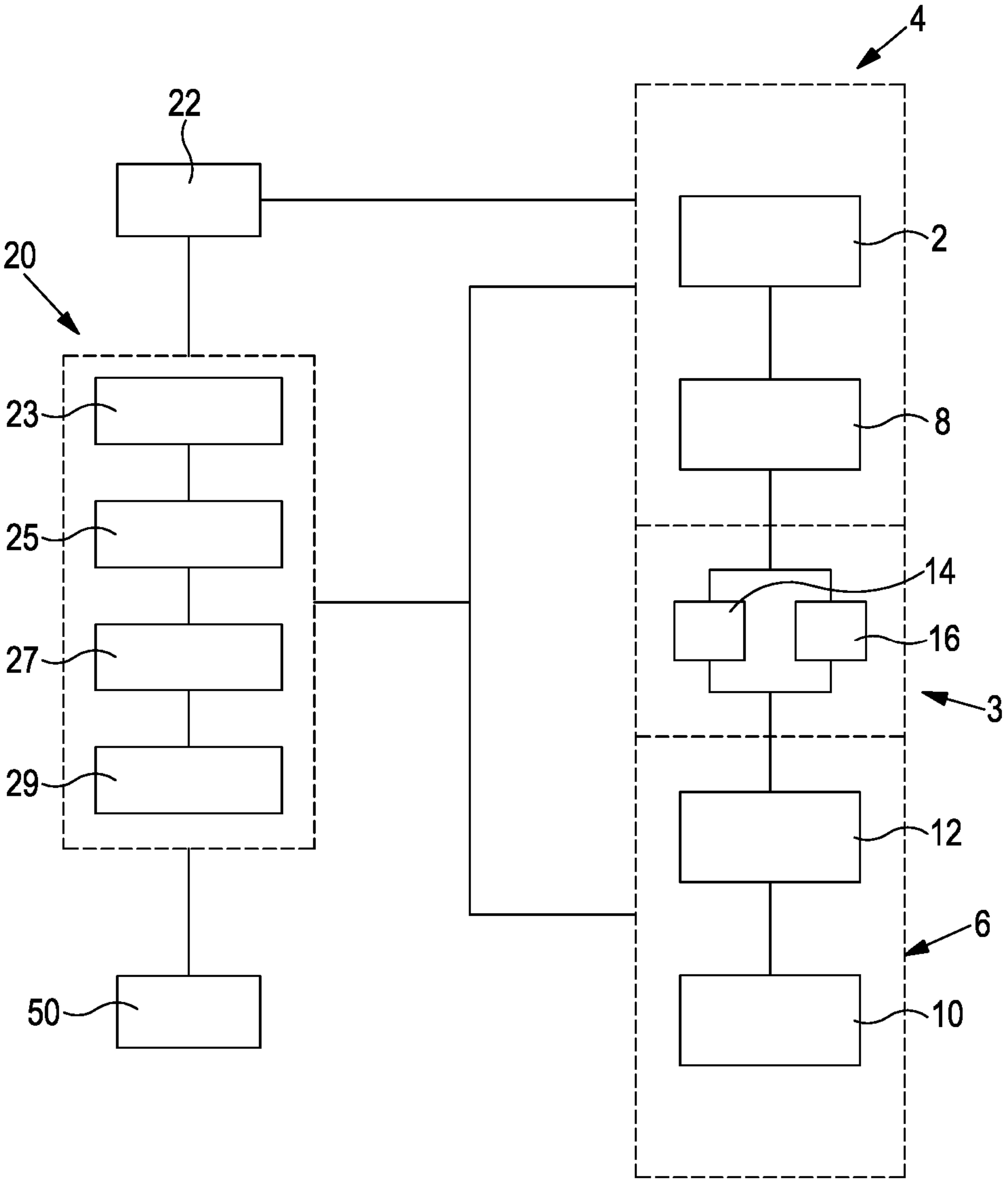

FIG. 8

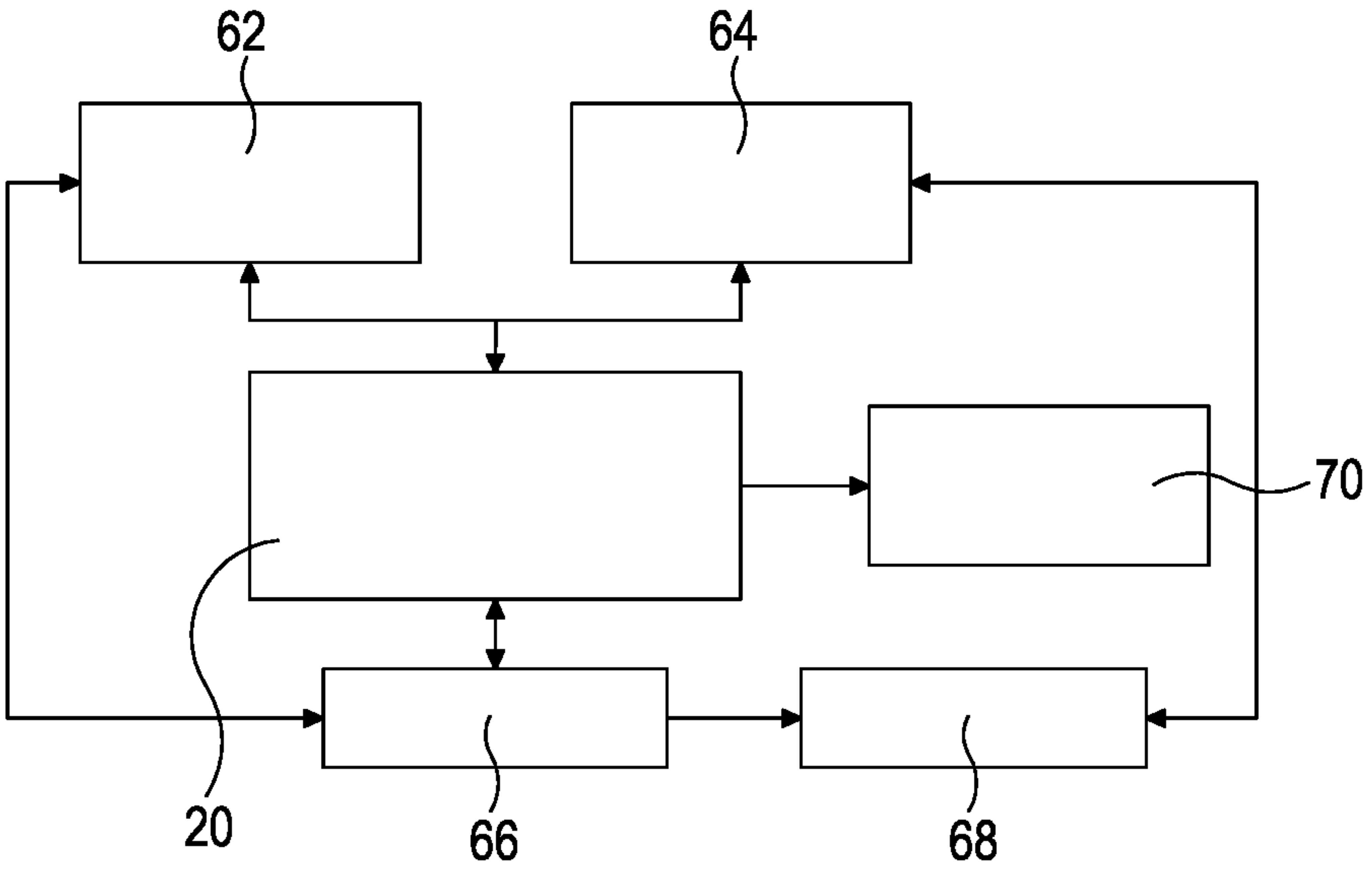

FIG. 9

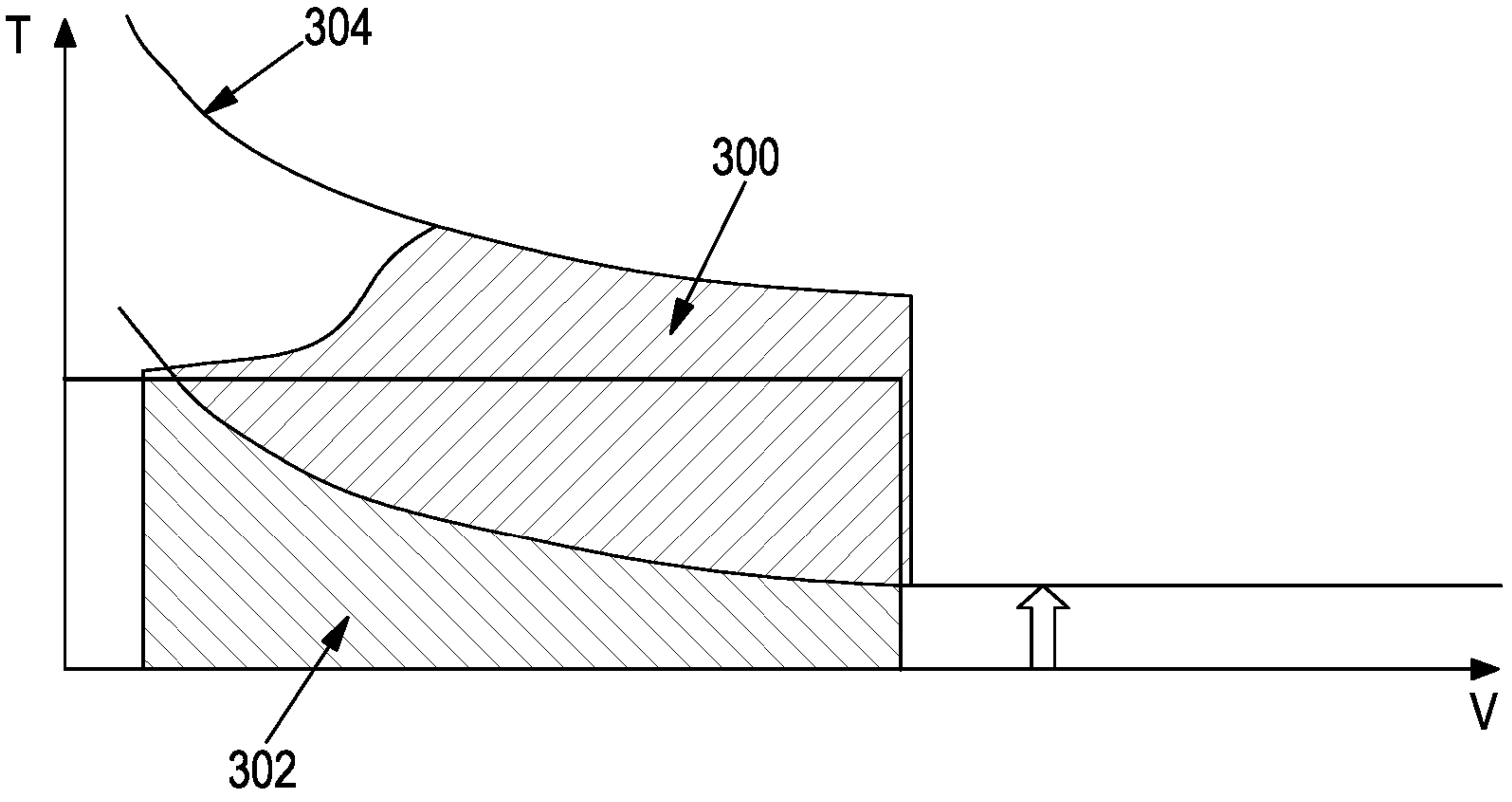

FIG. 10

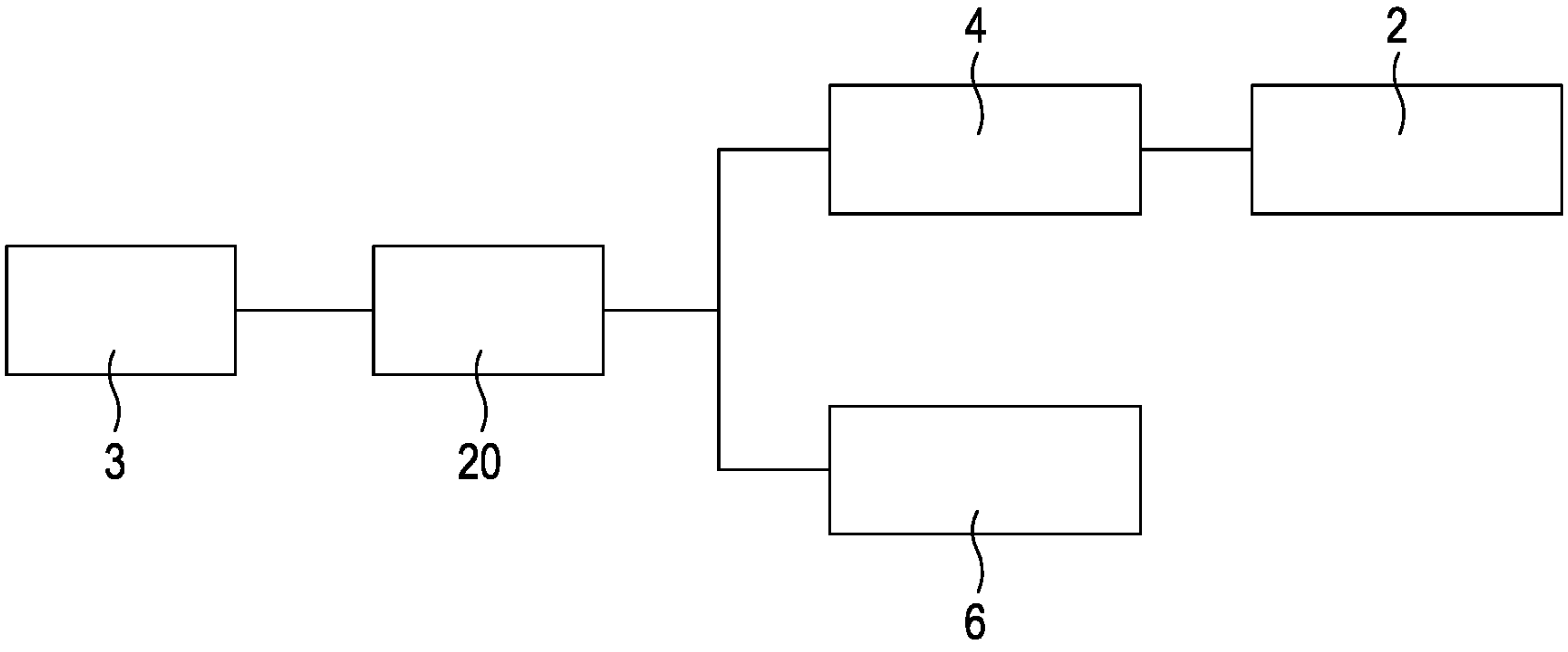

FIG. 11

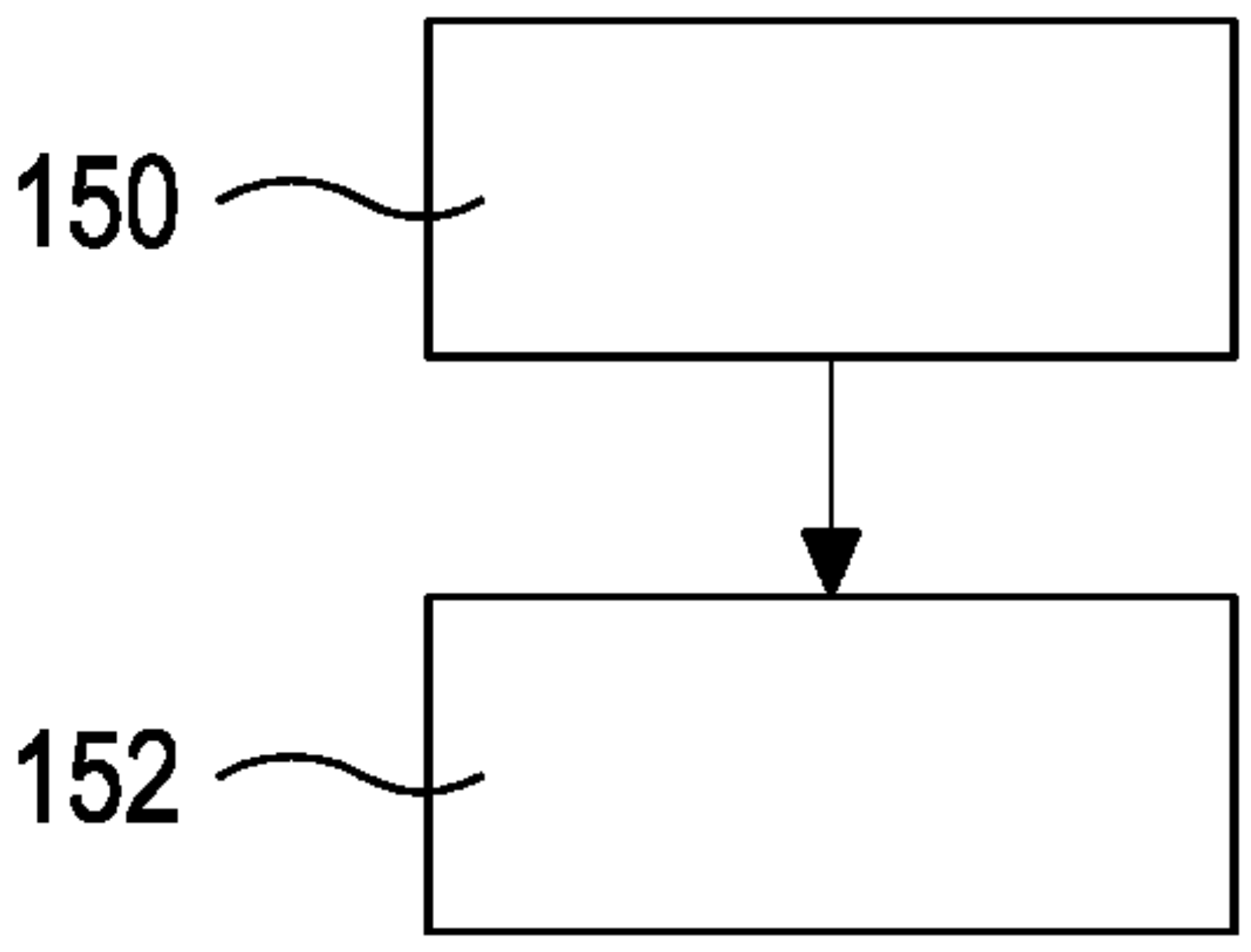

FIG. 12

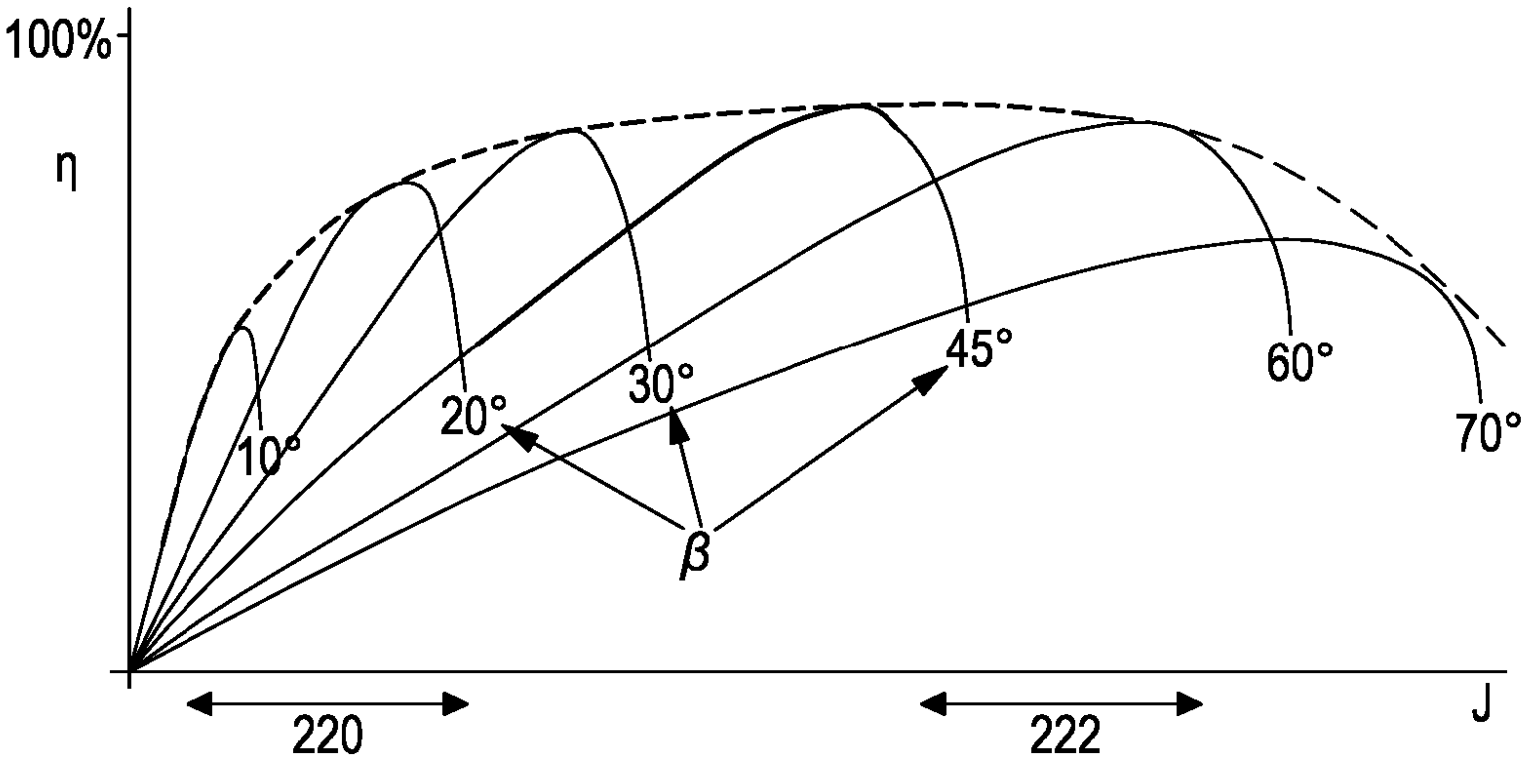

FIG. 13

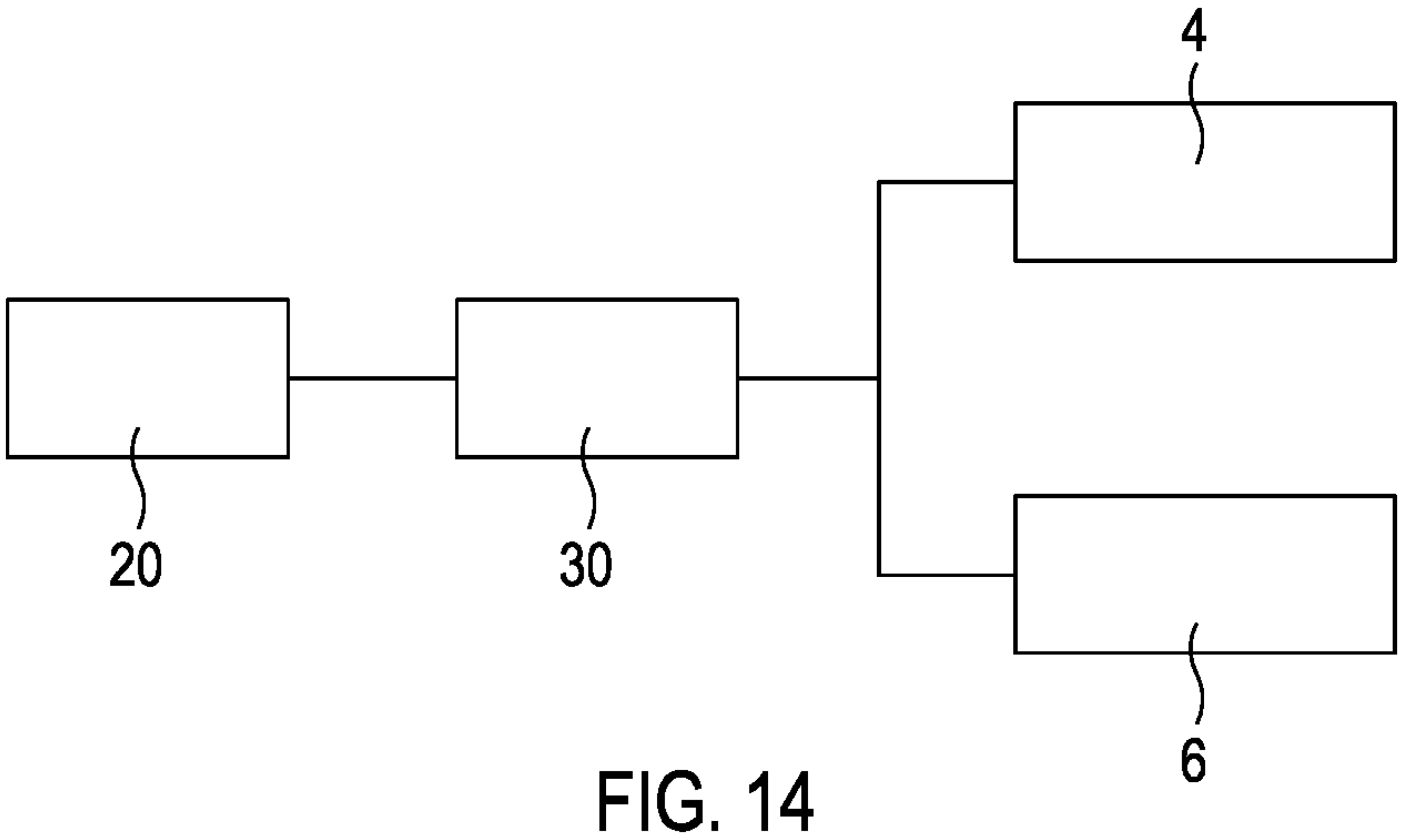

FIG. 14

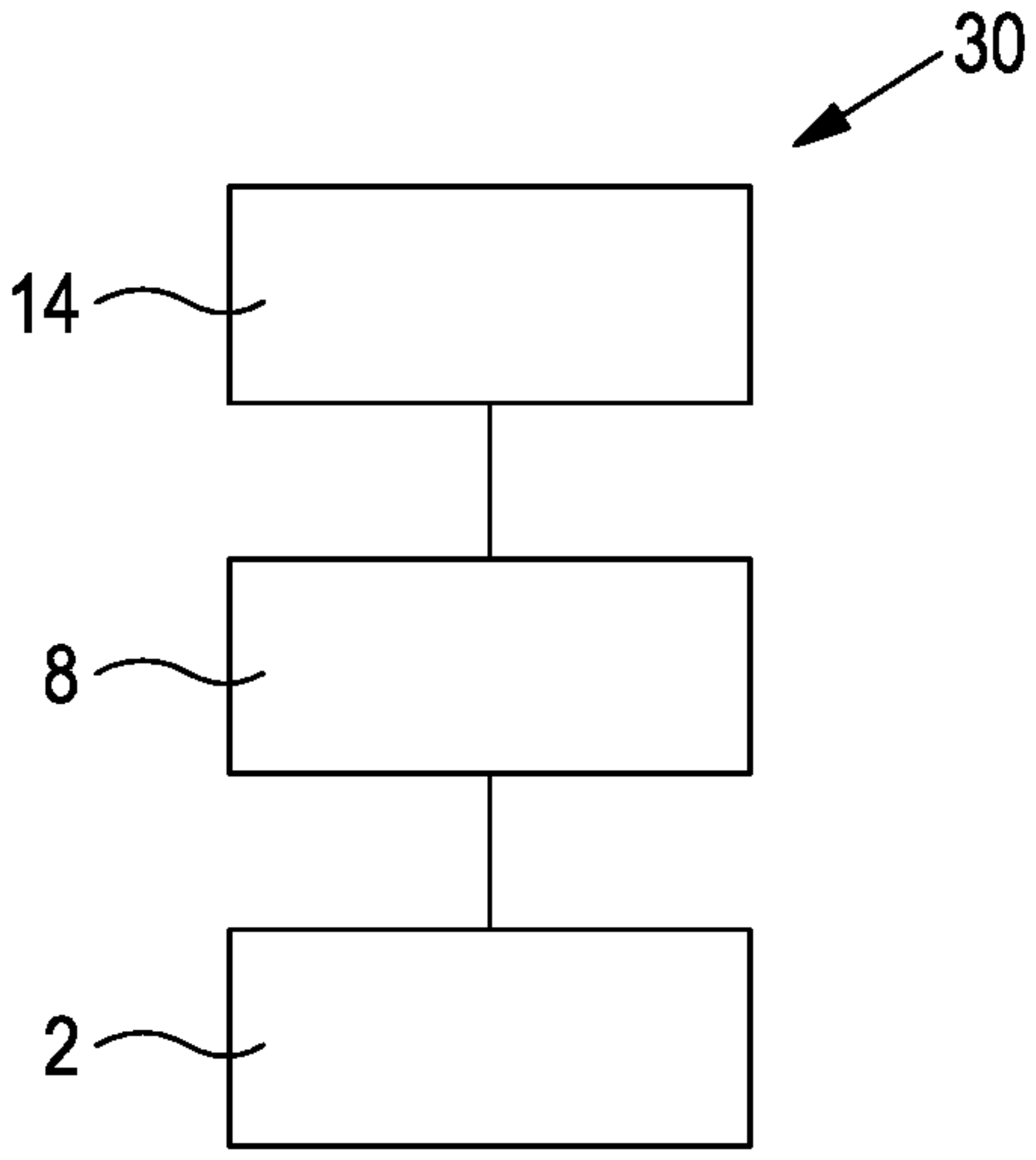

FIG. 15

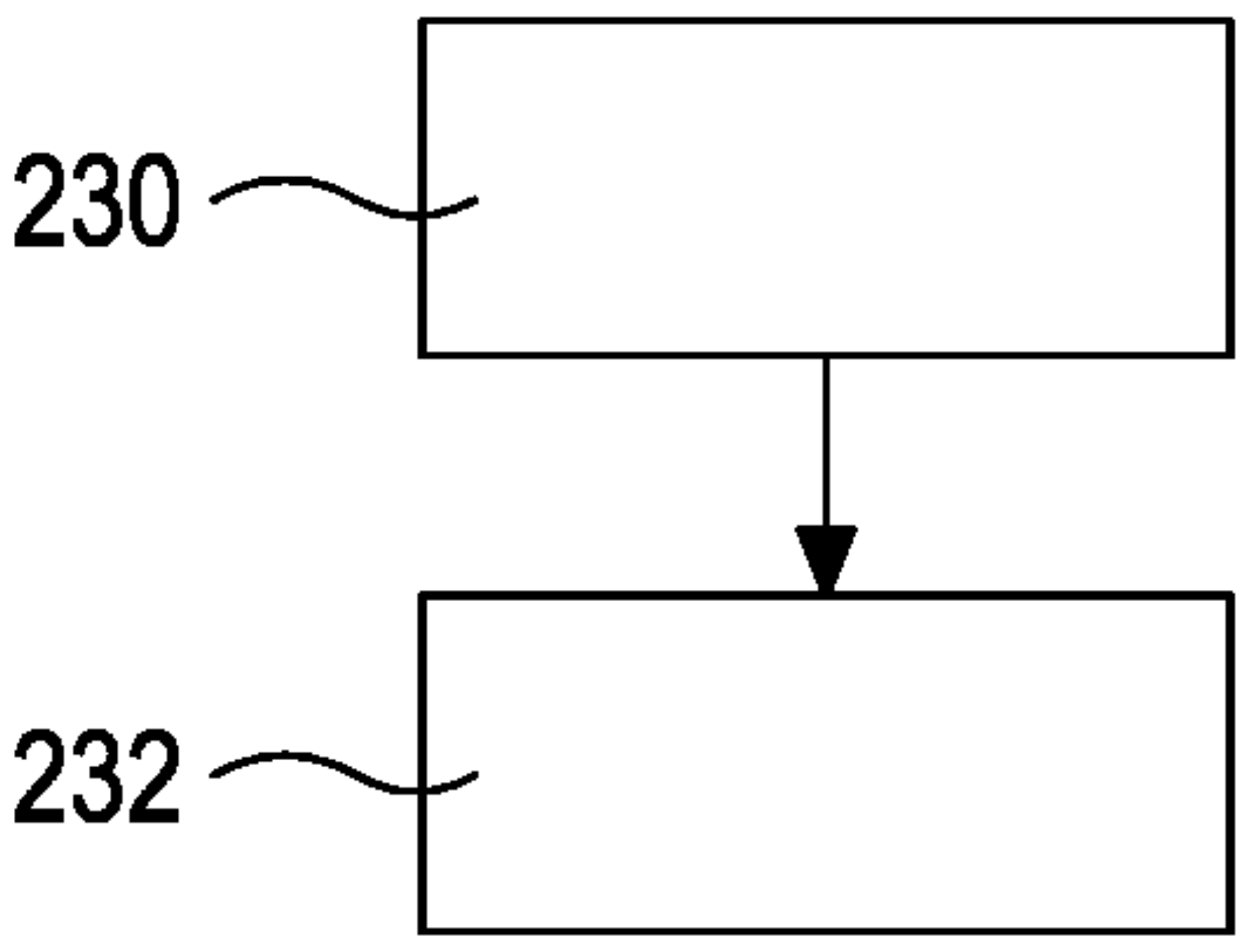

FIG. 16

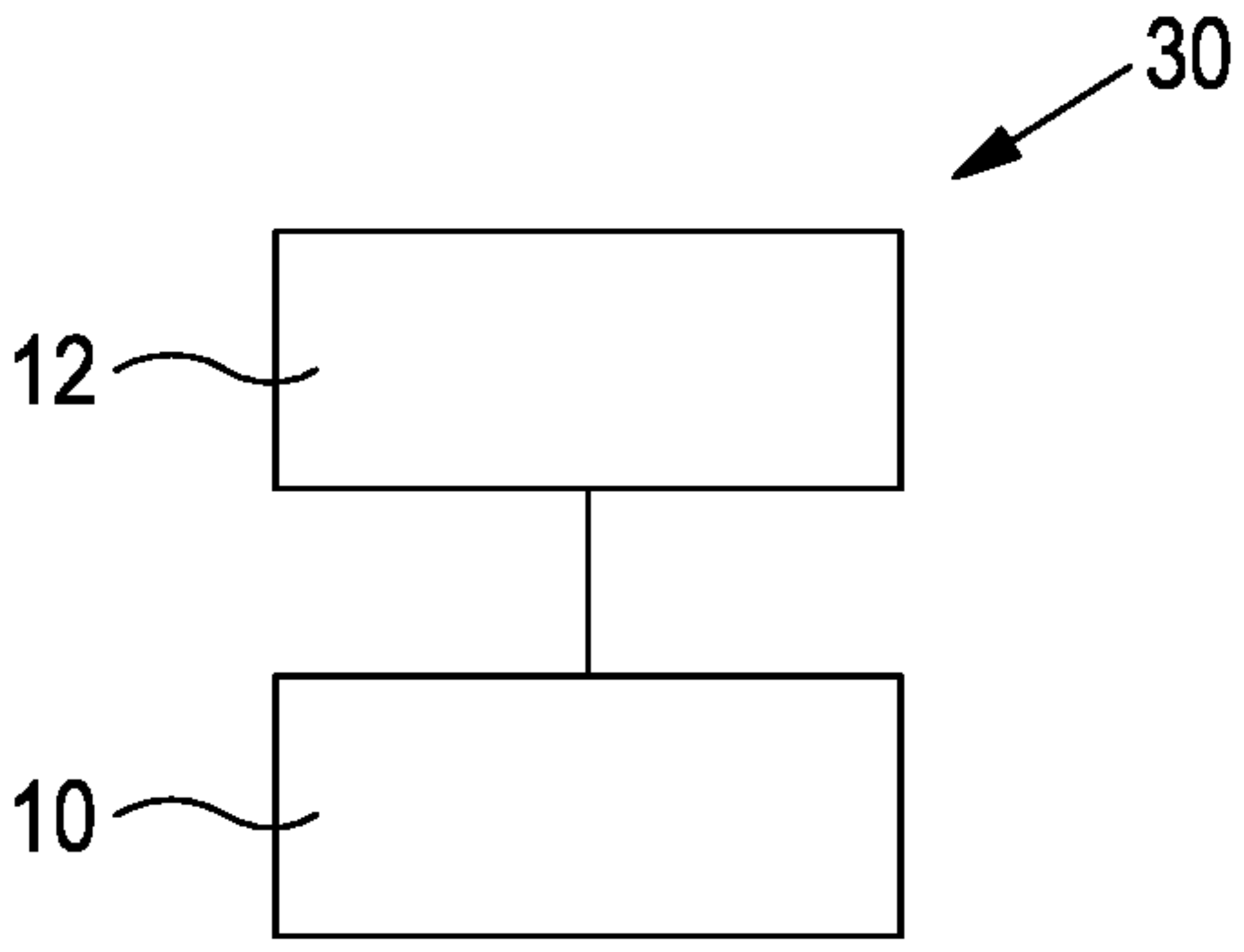

FIG. 17

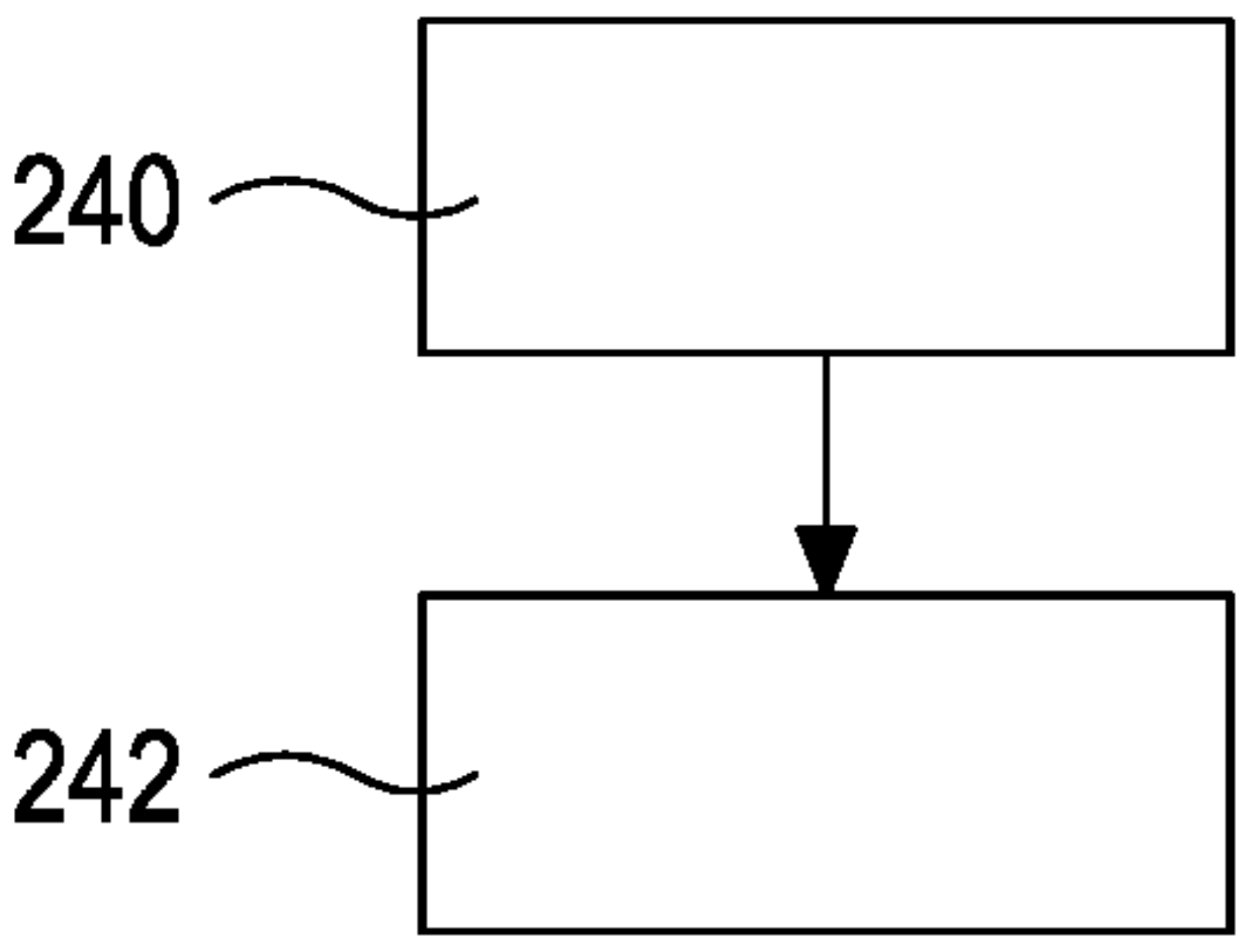

FIG. 18

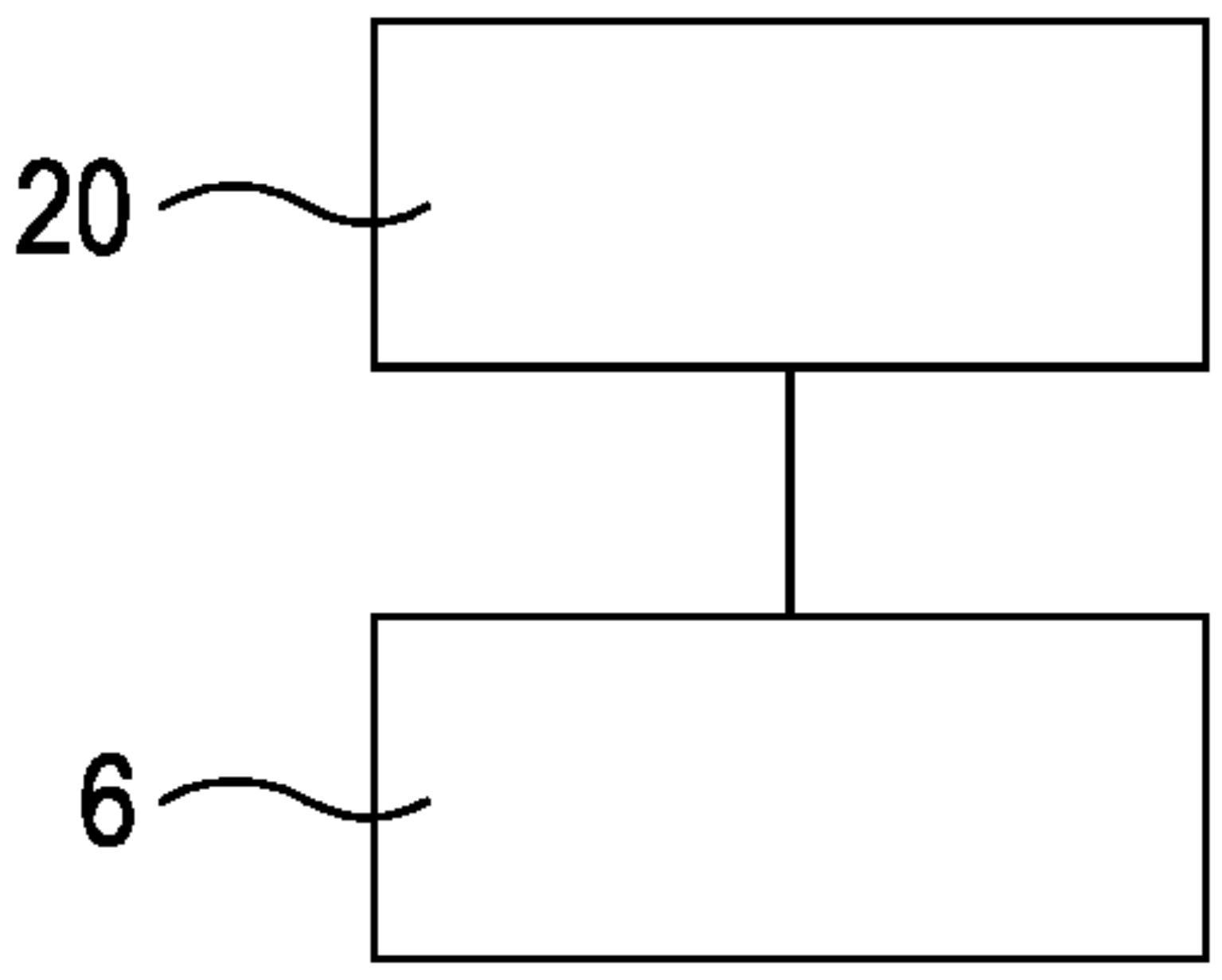

FIG. 19

FIG. 20

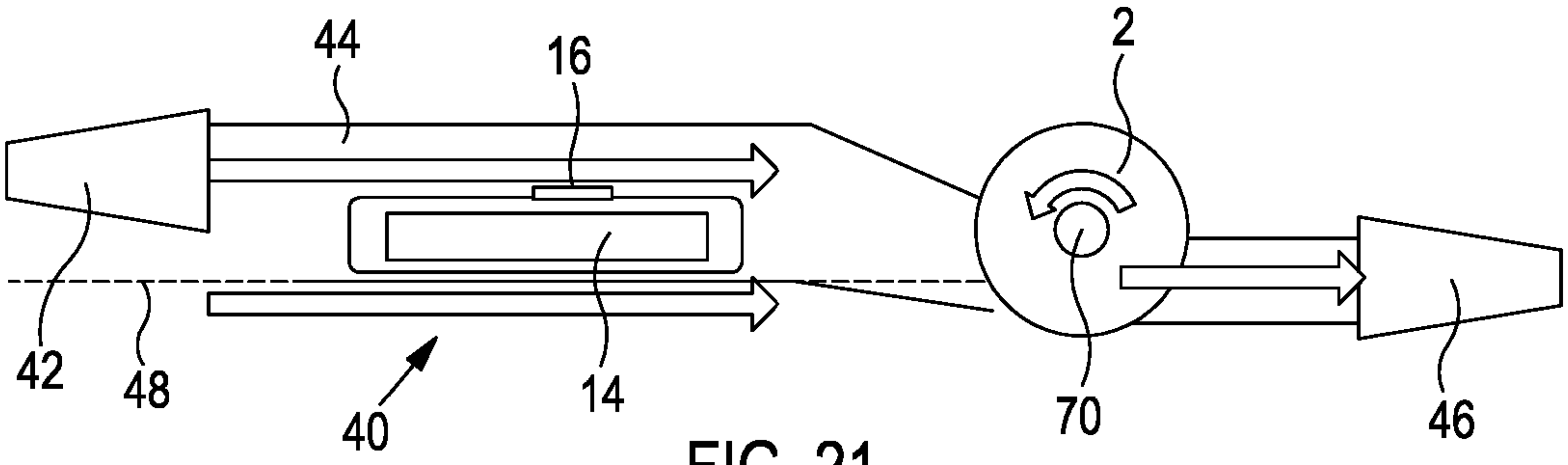

FIG. 21

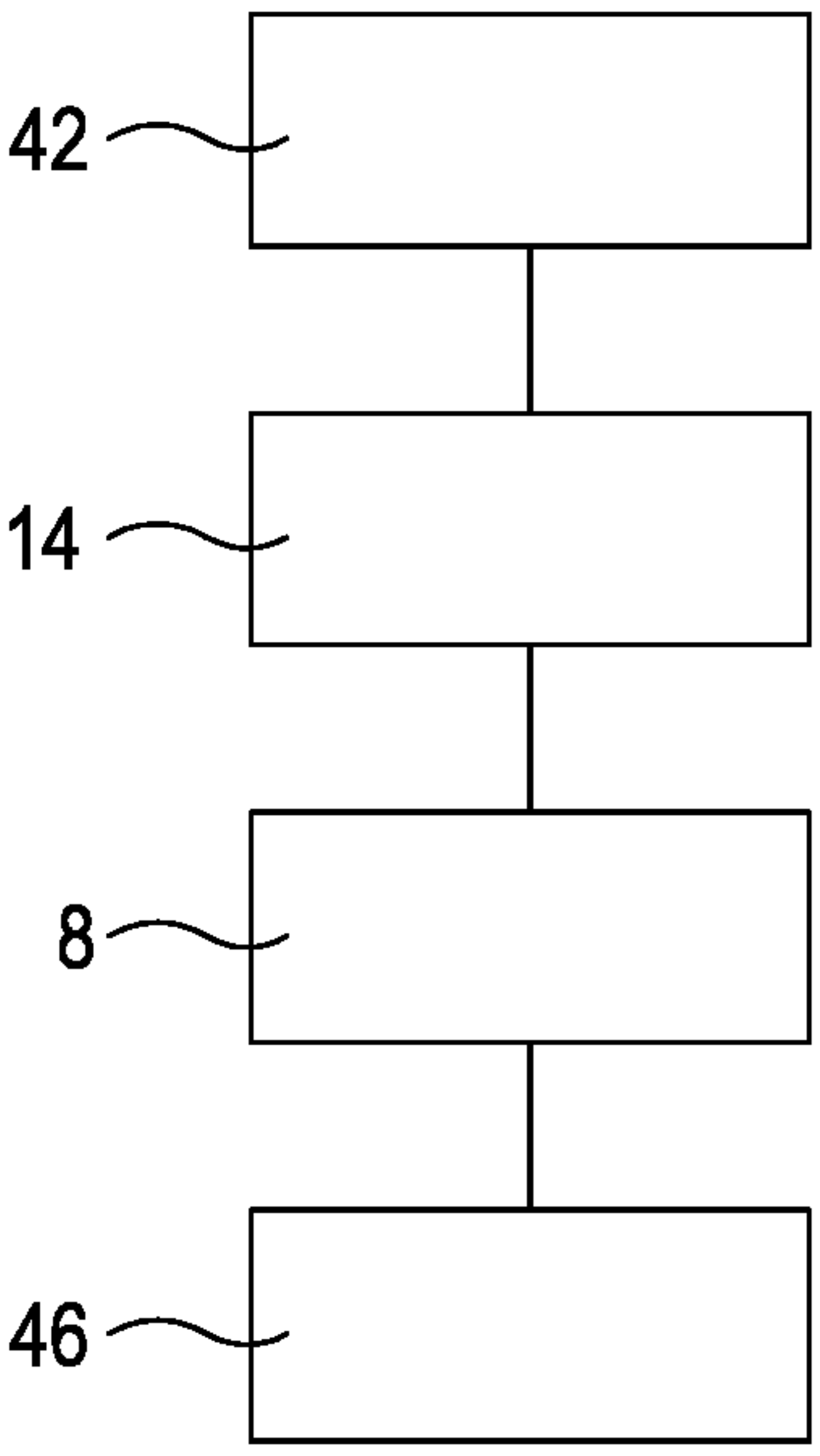

FIG. 22

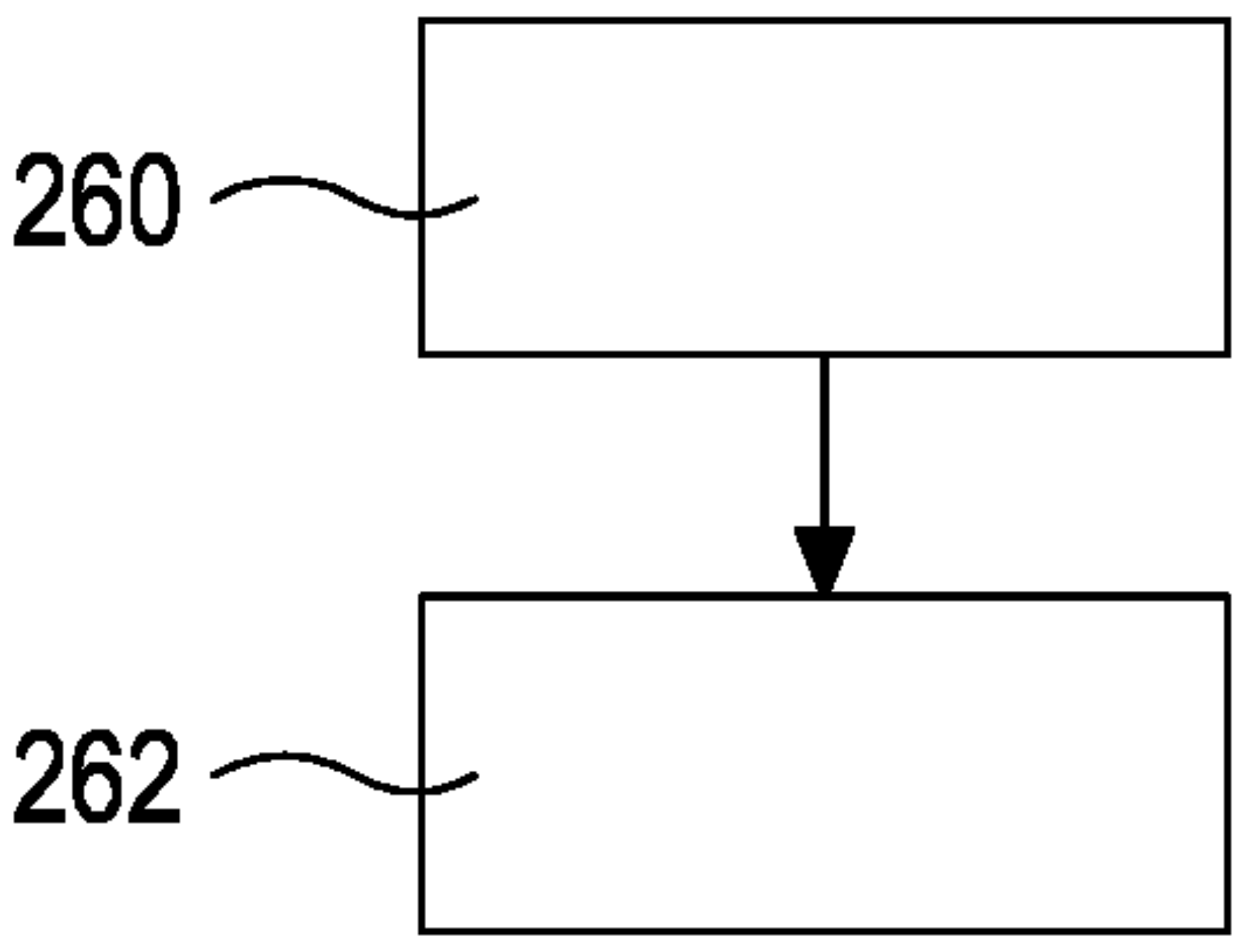

FIG. 23