Transmission type parallel to ship with hybrid power plant

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Abstract. The kinematic scheme of a two-stream transmission is considered, which makes it possible to implement the principle of using two engines (including those using different physical principles and having different energy characteristics) and to implement the idea of designing a hybrid power plant, including one adapted for operation on a driverless ship. The result of the research is the structural diagram of the transmission, the kinematic diagram of the summing gear in its composition and proposals for the implementation of the main units of the summing gear. The gearbox allows for smooth connection or disconnection of selected motors to the payload. The considered power plant combines an internal combustion engine and a traction motor. The main benefit is increased reliability through redundant motors. Improvements in efficiency are expected by ensuring consistent engine performance. The composition, the kinematic diagram, the principle of the transmission are proposed. The equations describing the kinematic and force relations in the summing gear are considered. The used method of kinematic and force analysis has been tested in the machine-building industry in relation to planetary gears as part of highly loaded transmissions of wheeled and tracked vehicles. References are given to technical solutions that make it possible to implement the proposed transmission based on the technological capabilities mastered by Russian manufacturers. The proposed scheme seems to be promising for use on ships for various purposes, including military boats, in the power plant of which a gas turbine engine is used.

1. Introduction
The use of a pair of energy sources (heat engines) with the same operating parameters today can be considered as a reliably tested approach in shipbuilding. As an example, we can cite the principle of using diesel engines combined into a “diesel-gear unit” [1].

The development of this principle implies that the prime movers can use different physical principles. For example, the engine used in the normal mode of motion can operate according to the diesel thermal cycle, and in the forced modes the ship also uses the additional energy of a less economical gas turbine power plant [2]. For example, an economical "diesel" can be used on the march, and the summation of the energy of a diesel engine and a gas turbine - in an extreme mode.

The principle of using “electromechanical transmission” on ships is also classic, when the energy of a heat engine is converted completely into electrical energy and is realized with the help of a propulsion device [1–3]. This approach is currently justifying itself from the standpoint of energy efficiency, since the "electric transmission" of the ship is quite successfully competing with the mechanical transmission.

However, the principle of parallel use of a heat and electric motor opens up more possibilities than sequential conversion of thermal energy into electrical energy:
An important advantage of a mechanical transmission is the required presence of a mechanical connection between the thermal (or electric) engine and the propulsor. Refusal of such a connection (for example, principles [4, 5]) determines the potential vulnerability of the control object to external influences.

A main weakness of driverless aquatic and terrestrial vehicles is the lack of prompt repair when possible in penetration of failures. At a critical moment there are no qualified engineers, able to solve the problem. For the power plant, this situation means the loss of mobility and inability to complete the task. Therefore, the use of a parallel-type hybrid power plant consisting of an internal combustion engine (ICE) and a traction electric motor can increase the ship's autonomy by providing duplication of the internal combustion engine and a traction electric motor.

As a side positive effect, one can consider the possibility of implementing a forced mode, when the internal combustion engine and the traction electric motor operate in parallel at maximum power. The question of the efficiency of such a power plant is debatable: much depends on the quality of control algorithms and the actual situation. An obvious disadvantage of the concept is the complication and increase in the cost of the power plant, an increase in its mass. This disadvantage is compensated by the expansion of the operational properties of the hybrid power plant.

This article researches a variant of the kinematic transmission scheme that ensures the operation of a parallel-type hybrid power plant.

2. Materials and methods
The object of the research was the structural diagrams of hybrid power plants and kinematic diagrams of summing gearboxes adapted for use on ships. At various stages of the work, theoretical methods (synthesis, abstraction, generalization, deduction, analogy, computer modeling) and empirical methods (description, comparison) were used.

3. Results of theoretical research
Transmission scheme for hybrid propulsion parallel type.

A simplified kinematic diagram of the transmission is shown in Figure 1. The predecessors of such a technical solution are proposals [6, 7] in the field of designing tracked and wheeled vehicles.

![Figure 1. Simplified kinematic transmission diagram: 1, 2 - power supply from engines; 3, 4 - gearboxes of the input transmission; 5 - reducer of the output transmission; 6 - power diversion to the load; T₀, T₁, T₂ - controls.](image)

The power plant consists of two engines (the power supply from them is shown – 1, 2) and the systems serving them.

One engine is a diesel internal combustion engine with an electronic control system (for example, Common Rail), the other is an asynchronous traction electric motor.
The use of a diesel engine with electronic injection control will make it easier to integrate into the on-board network, for example, using CAN protocols.

The use of an on-board network is inevitable on an unmanned vessel, when it is required to provide control of the electronic control system over all important components and assemblies.

It is possible to use any other heat engine (running on gas, petrol, fuel oil, etc.; a diesel engine with individual high-pressure fuel pumps, with pump injectors; a gasoline rotary piston engine; a gas turbine engine, etc.), if its system control can work as part of the on-board network.

The supply voltage of the traction electric motor is advantageously chosen high, according to the experience of designing military tracked vehicles («Puma», Germany) - about 750 V. With this supply voltage, the traction electric motor will be quite compact.

The motors are connected through 3, 4 gearboxes.

For internal combustion engines, it is advisable to provide at least a reverse in the gearbox. Other modes of operation of the gearbox can be borrowed from the practice of designing ships: A hybrid power plant can be built on the basis of an already developed structure based on an internal combustion engine.

For a traction electric motor, it is rational to use a gearbox with two gears to reduce its weight and size characteristics.

The combination of the power streams from the motors takes place in a gearbox consisting of two planetary gear sets.

Planetary gears are characterized by an internal gear ratio or kinematic parameter (gear ratio from the sun gear to the epicyclic gear when the carrier is stopped). The practice of designing power transmissions based on planetary gear sets [8] narrows the range of values of the kinematic parameter for simple planetary mechanisms (Figure 1) to approximately (–1.6) … (–4.5). There are other designs of planetary mechanisms, including those with a positive value of the kinematic parameter, but in Figure 1 the option seems to be optimal from the point of view of ensuring maximum torque reduction.

The gears of the rows are preferably made involute spur teeth (with a sufficiently high efficiency, the axial loads on the bearings of the supports are reduced).

Sun gears are connected to the motors. The common carrier allows one to take power. The control is carried out by turning on the brakes (T1 and T2) associated with the epicycles of the corresponding planetary gear sets. If the brake is on (there is no slipping in it), the selected motor is connected to the load. The gearbox controls can be configured as hydraulic disc brakes. For capacities up to about 750 kW in domestic transport engineering, there are proven design solutions and materials [8]. The best solution seems to be the use (with engine power up to 1500 kW) of a steel-metal-ceramic friction pair on a copper basis. Such discs have high durability, there is no self-seizing phenomenon for them.

Using brakes in combination with a planetary gear set is preferable to using clutches. The load on the brake is less and it can be made more compact.

The pressure in the drive system is controlled by an electronic-hydraulic control system [8, 9]. Various pressure control algorithms have been researched and realized - from elementary (static oil supply) to complex (pulse-width modulation of fluid pressure) [9]. The nomenclature of working fluids (oils) [8, 10, 11] has been worked out and this nomenclature is expanding. For transmissions designed for high power, it is advisable to use the materials recommended in research paper [8].

Brake T0 is designed to stop the output shaft (connected to the row carriers) of the gearbox.

If we complicate the design of the gearbox (add a blocking clutch between the shafts connected to the motors), then the traction electric motor can be used as a starter when this clutch and brake T0 are turned on. Such solution is possible, but does not seem appropriate, because standard ICE starters are compact and reliable.

An energy source is required to power the traction electric motor. As such, lead-acid storage batteries and a voltage converter with the required characteristics can be used. But at present, domestic manufacturers have mastered the production of more efficient energy storage devices based on
ionistors. The method for calculating the parameters of an ionistor storage as applied to a ground transport vehicle is given in [6]. Charging the storage device is advisable from an external electrical network when the ship is at rest. Recharging is carried out from an internal combustion engine operating in a stationary mode. In this regard, it is necessary to provide for the installation of a generator connected to the internal combustion engine and a rectifier unit.

The reducer in the load branch 5 (Figure 1) allows to adjust the transmission of the m wareing transmission based on the specific situation. In principle, this gearbox may not be available.

Table 1 lists the main operating modes of the power plant and included controls.

Let us consider the possible modes of operation for the circuit implemented in Figure 1 based on the diesel and traction electric motor.

1. The main mode is the use of a traction electric motor (which will provide less noise): the brake of a row connected to the traction electric motor, for example, T2, is turned on. The internal combustion engine works primarily to recharge the onboard power source and can be turned off. In this mode, the internal combustion engine is advisable to use in the mode of maximum efficiency.

2. Standby mode - using the internal combustion engine (an increase in fuel consumption is expected, it is advisable to use the mode if the traction electric motor fails): the brake of the row associated with the internal combustion engine is on, for example, T1. The internal combustion engine can work partially to recharge power sources or, including at full power, to drive the propeller (propellers).

3. Maximum power mode (forced mode) - the internal combustion engine and the traction electric motor operate in parallel: brakes T1 and T2 are engaged in the transmission. The mode is used to obtain maximum power on the propeller shaft.

4. Scrolling mode - using a traction electric motor for scrolling the internal combustion engine shaft, for example, when starting. Brake T0 is on, power is not supplied to the output from the transmission.

| Mode          | Included the elements management | Used engines |
|---------------|----------------------------------|--------------|
| Main          | T1                               | 1            |
| Spare         | T2                               | 2            |
| Forced        | T1 and T2                        | 1 and 2      |
| Scrolling     | T0                               | 1 and 2      |

The scrolling mode, in principle, makes it possible to abandon the electric starter for the internal combustion engine. When a gas turbine and a diesel engine are used in the power plant, the transmission modes are similar.

1. The main mode is the use of a diesel engine as a more economical engine. The GTE is turned off and its shaft is stopped. The mode is used on the march when the maximum speed of the vessel is not required.

2. Standby mode - using a gas turbine. In most cases, this mode is not justified due to the increased fuel consumption, but it can be used when it is necessary to obtain a high speed of the vessel, for example, during combat maneuvers.

3. Maximum power mode (boost mode) - both motors are used in parallel. The mode is designed to obtain maximum power on the propeller shaft.

4. Scrolling mode - if necessary, the diesel engine can be used to scroll the GTE shaft. Brake T0 is on, power is not supplied to the output from the transmission. Nevertheless, it is advisable to make a regular start of a gas turbine engine from an electric starter.

The kinematics of the transmission is described by the following equations (the basic equations of the kinematics of planetary mechanisms are a kind of Willis equations) [8, 12, 13].

Let us introduce the following about the values of angular velocities:

\( \omega_x \) - for the output link of the gearbox associated with the carriers of both rows;
\( \omega_{01}, \omega_{02} \) - for sun gears indirectly connected with motors 1 and 2;
\( \omega_{T1} \) and \( \omega_{T2} \) - for epicyclic gears included in the rows, connected, respectively, with engines D1 and D2.

Let us designate \( k_1 \) and \( k_2 \) - kinematic parameters of three-link planetary mechanisms, the sun gears of which are indirectly connected with motors 1 and 2.

Then the gearbox kinematics can be described by the equations:
\[
\begin{align*}
\omega_{01} &= k_1 \omega_{T1} + (1 - k_1) \omega_x; \\
\omega_{02} &= k_2 \omega_{T2} + (1 - k_2) \omega_x;
\end{align*}
\]

If we take constant angular velocity of one of the sun gears \( \omega_{01} = 1 \); then the angular velocity \( \omega_{02} \) is an independent parameter and can be expressed in fractions of \( \omega_{01} \).

Additionally, you should set the laws of motion of the links associated with the controls: when the brake is turned on, the angular velocity of the links associated with it is zero.

Then, when the traction electric motor and the internal combustion engine work together, equality must be observed:
\[
\omega_{01}/(1 - k_1) = \omega_{02}/(1 - k_2).
\]

Torque in the output unit composed of moments on the carrier of radiation of a respective planetary rows. Moments in ulcerative s s planetary gear sets are determined based on the traditional equilibrium equations \([8, 12, 13]\).

Let us introduce the notation for the moments:
\( M_x \) - gear on the output unit associated with the guide both p i rows;
\( M_{01} \) and \( M_{02} \) - on sun gears, indirectly associated with motors 1 and 2;
\( M_{T1} \) and \( M_{T2} \) - on the epicycles of the rows, indirectly associated with engines 1 and 2.

The moments on the brakes associated with the listed epicycles will be equal to the moments on the epicycles, but have the opposite sign.

Then on any operating mode:
\[
\begin{align*}
M_x &= [D_1 (1 - k_i) M_{01} + D_2 (1 - k_i) M_{02}]; \\
M_{T1} &= -k_1 M_{01}; \\
M_{T2} &= -k_2 M_{02};
\end{align*}
\]

In this record, \( D_{1,2} \) is a coefficient that takes values 1 if the corresponding control is enabled, or 0 if the control is disabled.

At partial load of the hybrid powertrain: \( D_i = 0 \) or \( D_i = 0 \).
In forced mode: \( D_1 D_2 D_{12} D_{22} = 1 \).

Ensuring the joint operation of the engines is carried out by selecting the gear ratios of the transmission branches.

Considering modern publications \([14–17]\), we can conclude that the Russian industry today has technologies that allow you to create a traction electric motor and energy storage devices that can provide a sufficient resource and reliability when working in a transmission, operating in severe conditions.

The variants of the proposed transmission can be adapted for use on ships for various purposes, including driverless.

**4. Conclusion**

Thus, there is reason to expect that the proposed set of modernization measures will lead to an improvement in the following operational properties of the chassis.

1. The use of a parallel-type hybrid power plant on a driverless ship will improve its reliability.
2. In transport engineering (design of high-speed tracked vehicles), there is a set of methodological and technological solutions (materials, manufacturing technologies for individual units) that can be used to create such a power plant.
3. The electrical, mechanical and electronic components necessary for the creation of a hybrid power plant are already being produced by the domestic industry, and the problem of import substitution, in principle, seems to be solved in this case.
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