Conceptual design Of Hybrid Scooter Transmission With Planetary Gear-Train

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List of abbreviation

1) Ci: engine idling clutch
2) \( W_i \): angular velocity of the input member
3) \( W_j \): angular velocity of the output member
4) \( W_k \): angular velocity of the remaining member
5) \( R_{F1} \): speed ratio of the one-dof PGT
6) \( R_{F2} \): speed ratio of the two-dof PGT
7) \( r_{sp} \): speed ratio of the split power system
8) \( r_m \): speed ratio of the split power system(electric motor mode)
9) \( r_e \): speed ratio of the split power system(engine mode)
10) \( r_g \): speed ratio of the electric motor/generator to the engine
11) \( r_p \): speed ratio of the split power system(power mode)
12) \( r_{reg} \): speed ratio of the split power system(regenerative braking)
13) \( r_{fd} \): speed ratio of the final reduction drive
14) \( Z_s \): no. of teeth of sun gear
15) \( Z_r \): no. of teeth of ring gear
16) \( P_{out} \): output power of the hybrid scooter
17) \( T_{out} \): output torque of the hybrid scooter
18) \( P_m \): power of the electric motor
19) \( T_m \): torque of the electric motor
20) \( \eta_{F1} \): efficiency of one-dof PGT
21) \( \eta_{fd} \): efficiency of final drive
22) \( P_e \): output power of the engine
23) \( T_e \): output torque of the engine
24) \( \eta_{sp} \): efficiency of split power system
25) \( P_{reg} \): regenerative braking power
26) \( T_{reg} \): regenerative braking torque
27) \( P_b \): braking power of the scooter
28) \( T_b \): braking torque of the scooter
Hybrid scooter transmissions utilizes the concept of a split power system consisting of a one degree-of-freedom (dof) planetary gear train (PGT) and a two-dof PGT with the ability to sum power from two sources, a gasoline engine and an electric motor. A planetary gear train consists of a centre arranged sun gear(s), a ring gear(r) and several planetary gears in between the sun and the ring mounted to the planet carrier(c). With the proper use of PGT, it can be operated either as a battery-powered electric scooter, or as a gasoline engine scooter traditionally, or a combination of both. This split-power system can be classified as an input-coupled system or an output-coupled system. One shaft of the gear train is linked to the power input side of an input-coupled system, as shown in Fig. 2(a); while the other shaft of the gear train is linked to the power output side for an output-coupled system, Fig. 2(b). One of the two-dof PGT members and the two coupled rotating members can be linked to the two power sources of the gasoline engine (E) and electric motor/generator (M/G), and one output member to the rear wheel (W) of the hybrid scooter.

![Fig.2 Representation of split power system](image)

**Configuration Of The Transmission System**

![Fig.3 Output-coupled configuration of the transmission system of the hybrid scooter](image)
Working

Five operating modes of this design for the hybrid scooter applications can be achieved: electric motor mode, engine mode, engine/charge mode, power mode and regenerative braking mode.

**Electric motor mode**
When starting, by using a control device keeps the gasoline engine stopped; the electric motor alone transmits power via the one-dof PGT and final reduction drive for moving the scooter.

**Engine mode**
When the electric motor drives the scooter at medium speeds, a control device starts the gasoline engine. The engine is accelerated to a speed above the clutching threshold of the idling clutch Ci, so that the engine power is transmitted via the coupled arrangement by the one-dof PGT and two-dof PGT as well as the final reduction drive to drive the scooter.

**Engine/charging mode**
While the scooter moving at medium to high speeds and the battery power stored electricity runs low, the electric motor is switched to generator function. The electric motor/generator generates electricity recharging the battery controlled by a control device. At the same time, the control device regulates the load of the electric motor/generator according to the state of the engine.

**Power mode**
When maximum acceleration is needed or during hill climbing, while the scooter cruises driven by the engine, the electric motor is switched on. The electric motor power and the engine power are coupled together simultaneously to drive the scooter operating in the power mode. Since the electric motor is continuously mounted on the system, no sudden forces affect driving of the scooter.

**Regenerative braking mode**
When the scooter brakes or rolls downhill, the kinetic energy of the scooter is transmitted through the final reduction drive and one-dof PGT to the electric motor/generator. The electric motor is switched into a generator providing the braking effort to the scooter and charging the batteries.
Kinematic analysis

The speed ratio of a PGT is defined as the ratio of the output speed to the input speed with the remaining members of the PGT being relatively fixed. Letting RF2 be the speed ratio of the two-dof PGT as the input member i, the output member j and the remaining member k, we have

\[ R_{F2} = \frac{W_j - W_k}{W_i - W_k} \]  

(1)

For the one-dof PGT the speed ratio is

\[ R_{F1} = \frac{W_j}{W_k} \]  

(2)

In which \( W_i \), \( W_j \), \( W_k \) denote the angular velocities of the input, output and the remaining member of the two-dof PGT respectively. Dividing eqn (1) by \( W_k \) and substituting eqn (2) in that, we can find the speed ratio of the split power system \( r_{sp} \)

\[ r_{sp} = \frac{W_j}{W_i} \]  

(3)

\[ r_{sp} = \frac{R_{F1} R_{F2}}{R_{F1} + R_{F2} - 1} \]  

(4)

if the speed ratio of transmission is defined as the output speed to the input speed, the speed ratio of the five operating modes can then be derived in the follow equations:

\[ r_m = R_{F1} r_{fd} \]

\[ r_e = \frac{R_{F1} R_{F2} r_{fd}}{R_{F1} + R_{F2} - 1} \]

\[ r_g = \frac{R_{F2}}{R_{F1} + R_{F2} - 1} \]

\[ r_p = \frac{R_{F1} R_{F2} r_{fd}}{R_{F1} + R_{F2} - 1} \]

\[ r_{reg} = \frac{1}{R_{F1} r_{fd}} \]

In which \( r_m \), \( r_e \), \( r_p \) and \( r_{reg} \) are the speed ratio of the electric motor mode, engine mode, power mode and regenerative braking mode, respectively, \( r_{fd} \) is the speed ratio of the final reduction drive, and \( r_g \) is the speed ratio of the electric motor/generator to the engine as operating in the engine/charging mode.
Evaluation of the acceptable design-concepts for hybrid scooter-transmissions

(1) the speed ratio of the transmission is greater than zero because a scooter does not have a reverse gear; i.e. \( r_M > 0, r_E > 0 \)
(2) when the electric motor is serving as a generator the rotation direction is the same as serving an electric motor; i.e. \( r_G > 0 \)
(3) the speed ratio of the transmission operating in the electric motor mode is less than in the engine mode because the electric motor runs at start-up to reduce emissions; i.e. \( r_M < r_E \).

The speed ratio corresponds to the ranges of speed ratio of the one-dof PGT and two-dof PGT as \( 0 < R_{F1} < 1 \) and \( R_{F2} > 1 \), respectively. Here the ring gear, planet carrier and sun gear of the simple PGT are denoted by \( r \), \( c \) and \( s \), respectively, while speed ratios for each connection are shown in terms of ring/sun teeth \( R_0 = \frac{Z_r}{Z_s} \) on each gear train block.

Relationship of speed ratio

The top speed of the hybrid scooter occurs when the hybrid scooter is operating in the engine mode. If the speed ratio of the engine mode is estimated and the ratio between the two speed stages of the electric motor mode and the engine mode \( r_E/r_M \) is selected, the speed ratio of the electric motor mode can be calculated. Moreover, as depicted in Fig. 5(a), since the speed ratio of the electric motor mode equals the speed ratio of the one-dof PGT times the speed ratio of the final reduction drive, and then the speed ratio of two-dof PGT can be determined. Fig. 5(b) shows the speed ratio of the split power system, being a plot of the speed ratio of one-dof PGT against two-dof PGT. This figure depicts the ranges of the speed ratio of the engine mode for the four acceptable configurations corresponding to Fig. 3. The configurations as the speed ratio ranges of \( 0.5 < R_{F1} < 1 \) and \( 1 < R_{F2} < 2 \), for instance, the speed ratio of the engine mode is about greater than \( 0.7r_{fd} \). In the engine/charging mode, part of engine power is directed to the scooter; and the other part to the electric motor/generator for charging the batteries. As shown in Fig. 5(c), the speed ratio of the electric motor/generator to the engine is greater than one. To avoid the top speed of the electric motor is too high because of the top speed of a gasoline engine used in scooter is usually about 9000 rpm, the engine coupled an adjustment gear pair to reduce the top speed is required. Figure below shows acceptable designs of the hybrid scooter-transmission.
Fig. 4 Acceptable designs of the hybrid scooter transmission.
Fig. 5 Relationship of speed ratio
Transmission power performances

For the recognition the fundamental characteristics of the transmission power performance, the kinetic energy of the rotary masses of the drive train are neglected here. Once the mechanical efficiency of the drive chains is known the power performance of the hybrid scooter transmissions can be represented. In what follows, we compute the power and torque ratios for each of the five operating modes

**Electric motor mode**

In the electric motor mode, the power behavior is dependent on the one-dof PGT and final reduction drive. From Eqs. (4) and (9), the power and torque ratio of the electric motor mode can be written as

\[
|P_{\text{out}}| = \eta_{F1}\eta_{fd} P_m
\]

\[
|T_{\text{out}}| = \frac{\eta_{F1}\eta_{fd}}{r_m} T_m
\]

Here \( P_m \) and \( P_{\text{out}} \) denote the power of the electric motor and output power of the hybrid scooter, respectively. \( T_m \) and \( T_{\text{out}} \) are the input torque of the electric motor and output torque of the hybrid scooter, respectively.

**Engine mode**

In the engine mode, the power behavior can be characterized by the engine adjustment gear pair, the split power system, and the final reduction drive. The transmission power performance in the engine mode is described by

\[
|P_{\text{out}}| = \eta_{sp}\eta_{fd} P_e
\]

\[
|T_{\text{out}}| = \frac{\eta_{sp}\eta_{fd}}{r_e} T_e
\]

Here \( P_e \) and \( T_e \) denote the output power and torque of the engine.

**Power mode**

In the power mode, both the electric motor and gasoline engine drive the scooter simultaneously. Because of the structure of gear trains, the rotation speeds in this mode depend on the speed of either the electric motor or the engine but not both. The power performance can be expressed as

\[
|P_{\text{out}}| = \eta_{F1}\eta_{fd} P_m + \eta_{sp}\eta_{fd} P_e
\]

\[
|T_{\text{out}}| = \frac{\eta_{F1}\eta_{fd}}{r_m} T_m + \frac{\eta_{sp}\eta_{fd}}{r_e} T_e
\]
**Regenerative braking mode**

In this mode, with the engine idling clutch $C_i$ disengaged, the electric generator provides the braking efforts to the scooter. The power follow relations follow that of the electric motor mode occurring in the reverse sense. The regenerative braking power $P_{\text{reg}}$ and torque $T_{\text{reg}}$ are expressed as

\[
|P_{\text{reg}}| = \eta_{f1} \eta_{fd} \, P_b \\
|T_{\text{reg}}| = \frac{\eta_{f1} \eta_{fd}}{r_{\text{reg}}} \, T_b
\]

Here $P_b$ and $T_b$ are the braking power and torque of the scooter, respectively.
Conclusions

The purpose of this paper is to describe a new design concept for hybrid scooter transmissions. These new designs primary feature is to use a split power system that consists of a one-dof PGT and a two-dof PGT to combine the power of two power sources, a gasoline engine and an electric motor. The transmission described in this paper can provide a hybrid scooter to run five modes of operation. In the electric motor mode, the electric motor alone drives the motorcycle at start-up and for low speeds. In the engine mode, the engine alone drives the motorcycle after medium speeds. In the power mode, the electric motor and the engine drive the motorcycle simultaneously to achieve maximum power performance. In the engine/charging mode, the electric motor functions as a generator to charge to batteries, and it is possible to run the engine at an optimal operating condition by regulating the speed and load of the generator at the same time. In the regenerative braking mode, the electric motor is switched into a generator providing the braking effort to the scooter and charging the batteries. Potential advantages of these new transmissions include the use of only one electric motor/generator, need not use clutch/brake for the shift of the operating modes for easy control and low cost, and high efficiency. Additionally, the common advantages of a hybrid design such as regeneration of braking energy, engine shut down instead idling to reduce emissions, engine driving under high-load and low-specific-fuel-consumption conditions to reduce the low-load and high-specific-fuel-consumption driving time, etc. In this article, the proposed hybrid scooter transmissions are explained first; and the kinematics, power flow, and mechanical efficiency analyses are then accomplished for evaluation the transmission power performances. The results show that the hybrid scooter transmissions proposed here is practicable.
References