Design on ADES Based on IFTDEPMG and its Efficiency Test

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Abstract. The accelerator/decelerator is the key part of the electromagnetic suspension (EMS) for it bears the function of torque changer and of speed changer synchronously. This paper introduces the scheme and working principle of electromechanical suspension for armored vehicles firstly. Then, the requirements of the accelerator/decelerator of the electromechanical suspension (ADES) are introduced according to the characteristics of armored vehicles. The accelerator/decelerator of an involute few-tooth-difference external parallel moving gear is designed, and an accelerator/decelerator prototype is tested on the bench. The results show that the accelerator/decelerator of the involute few-tooth-difference external parallel moving gear (IFTDEPMG) has high efficiency in bidirectional transmission, which satisfies the transmission requirements of electromechanical suspension in both active and passive conditions.

Keywords: Armored vehicles; electromagnetic suspension; Involute few-tooth-difference external parallel moving gear; Bidirectional transmission with high efficiency.

1. Introduction
Compared to hydraulic or pneumatic suspension, electromechanical suspension has good characteristics. For example, the damping force is not affected by environmental factors (such as temperature); the system does not leak, quickly responds to the active/semi-active control and achieves the damping absorption and recovery of vibration energy in the semi-active control and passive states. All of these characteristics have garnered extensive attention from the automotive industry worldwide. With the development of all-electric vehicles, the electromechanical suspension will have good development and application prospects on vehicles, particularly tanks and armored vehicles with higher vibration amplitudes [1-4].

Among in all mechanical components of the electromagnetic suspension, the reducer is a key component for it used as a decelerator during it works in active mode. On the other side, it used as a accelerator during it works in semi-active mode and in passive mode. The planetary reducer is used in the Electromechanical Suspension System(ECASS) which has been the most typical active suspension. Its big transmission ratio enables it can achieves a good variable torque effect, which will greatly reduce the weight and size of its motor[2][5]. For four planetary wheels is used, its coincidence is about 4-5. This low coincidence is not enough strong to bear the big reciprocating impact resuled from the wheel, and so it resulted in low reliability such gear tooth fracture.

This paper first introduces the scheme and working principle of electromechanical suspension for armored vehicles. Then, an IFTDEPMG with high coincidence is designed based on the technical requirements of accelerators/decelerators in electromechanical suspension for armored vehicles. Finally, bench tests of the accelerator/decelerator in electromechanical suspension for armored vehicles are performed to examine the feasibility of an accelerator/decelerator of the IFTDEPMG.
2. Brief Introduction of the Electromechanical Suspension Scheme for a Tracked Vehicle

2.1. Electromechanical Suspension Scheme for a Tracked Vehicle

Figure 1 is a schematic diagram of the electromechanical suspension mechanism for a tracked vehicle. Here, the mechanical components of the electromechanical suspension mainly include a motion balanced mechanism composed of a torsion bar spring, a balance elbow, a connecting rod, and a pull arm; the accelerator/decelerator and electromagnetic actuator integrated to the motor. The electromechanical suspension arrangement is similar to the scheme of a torsion bar plus vane suspension arrangement, except the elastic element remains as the torsion bar, the vibration absorber is replaced by an accelerator/decelerator, and the rear electromagnetic actuator is composed of suction motors [4].

As the flexible element of a vehicle, the spring provides the static support and buffer function. The movement conversion mechanism converts the up-and-down bounce of the wheels into the rotary motion of the power input shaft in the electromagnetic actuator. The main function of the accelerator/decelerator is to achieve variable speed movements. The torque is reduced with acceleration in the passive condition and increased with deceleration in the active condition. The motor provides a damping force for the suspension in the passive or semi-active condition (which can be considered a shock absorber here). The energy recovery or feedback is realized to provide active control for the suspension in the active condition.

![Figure 1. The mechanism scheme of the electromechanical suspension in a trailed vehicle.](image1)

2.2. Working Principle

Figure 2 shows the working principle[4].

![Figure 2. Working principle of the electromechanical suspension.](image2)
In the semi-active or passive condition, the up-and-down bouncing of the wheel with respect to the vehicle body is converted into the acceleration movement by the movement conversion mechanism. The corresponding movement is transmitted to the electromagnetic actuator (the generator works as a damper in the semi-active condition or in the passive condition) to generate a three-phase AC. Then, the three-phase AC is converted to DC by a rectifying regulating circuit. The battery is charged with the DC, or the DC is used by the onboard appliances. In the active condition, the reversible rectifying regulating circuit converts the electric energy in the vehicle battery into a three-phase PWM pulse signal, which drives the electromagnetic actuator (driven by the motor in the semi-active condition) to rotate at high speed. Active control is realized by the reversed deceleration of the accelerator (used as a decelerator in the active condition) and the up-and-down bounce of the wheel relative to the vehicle body, which is caused by the movement conversion mechanism.

3. Design Requirements and Scheme of the Accelerator/Decelerator for the Electromechanical Suspension

3.1. Design Requirements of the Accelerator/Decelerator for the Electromechanical Suspension

Figures 1 and 2 show that the accelerator/decelerator, permanent magnet synchronous motor, and reversible rectifying circuit in the electromechanical suspension system are basically bidirectional components that bear the alternating load and extreme operating environment. In particular, the accelerator/decelerator operates at the front of the electromagnetic actuator to withstand the impact of an alternating load. As a key component of the electromechanical suspension[6-8], its requirements are as follows:

(1) The increasing (decreasing) gear ratio of the accelerator should be maximized to satisfy the requirements of semi-active generation and active driving. The torque and size of the motor should be minimized to satisfy the overall layout requirements.

(2) The bidirectional mechanical transmission efficiency should be maximized to convert the shock absorption energy into useful energy when it is used as passive suspension or semi-active suspension; when used as active suspension, the suspension action is controlled with the maximal conversion efficiency and maximal torque to achieve high vehicle anti-vibrating performance.

(3) The transmission should be steady and accurate and have a fast response to satisfy the active/semi-active real-time control requirements.

(4) The radial size should be suitable, and the axial size should be minimal to satisfy the overall layout requirements.

(5) The structure should be as simple as possible to reduce costs, and it should be reliable and easy to maintain.

3.2. Accelerator/Decelerator Design Scheme for the Electromechanical Suspension

At present, most gear transmission mechanisms have high mechanical efficiency when they are used as a decelerator. However, the transmission efficiency decreases when the transmission ratio increases when it is used as an accelerator, and it can even be self-locking, such as in a planetary gear decelerator[6-7]. The transmission ratio of the involute few-tooth-difference planetary gear decelerator is large, and its first-level deceleration ratio is up to 100. This decelerator has a simple structure, a small size and a lighter weight than an ordinary gear decelerator; its weight can be reduced by more than one third. In addition, it features smooth movement, easy-to-process tooth shape, and easy loading and unloading. In reasonable design, manufacturing, and lubrication conditions, the efficiency can be 0.85-0.91. Therefore, this decelerator has been widely used in many industrial sectors [9]. However, the transmission efficiency obviously decreases when the transmission ratio increases. Although a planetary gear decelerator and a gear transmission structure with few teeth are easy to process, the transmission efficiency hardly satisfies the electromechanical suspension transmission requirements when used as an accelerator.

Through the survey, IFTDEPMG, which is the variation of the few-tooth-differential gear transmission with a low pair replacing the high pair, is really an external parallel moving gear mechanism as shown in
Figure 3. Its transmission efficiency does not obviously decrease when the transmission ratio increases[10-12]. Therefore, IFTDEPMG can be used as an accelerator/decelerator for electromechanical suspension.

In addition, due to the slight deformation and large number of meshing teeth (usually more than 7-8 pairs), the maximum load on its main meshing gear is lower than that of the general planetary accelerator gear, and so it has higher carrying ability and overload ability for its inner external parallel moving gear mechanism [6–7]. These characteristics are very important to absorb reciprocating vibration and impact resulted from alternating load, which the electromechanical suspension accelerators of military vehicles withstand.

Since the installation of the electromechanical suspension in a vehicle’s body is limited by the lateral space in the vehicle, the axial dimension of the electromechanical suspension actuator cannot be too large. In this paper, an accelerator/decelerator gear design scheme is adopted as shown in Figure 4. To transmit the power of the mobile frames connected to several synchronizing external parallel moving gears on the same power shaft, an one-level fixed-axis transmission is added at the end of the external parallel moving gear. Figure 4 and 5 shows that the power of the planet frames H1 and H2 is transmitted to the output shaft Z6, which is connected to the rotor of the motor (generator) through two fixed-axis gears Z4 and Z5, to realize the confluence output after the power split in the passive condition and the split output in the active condition.

Figure 3. Mechanism scheme of the external parallel moving gear.

Figure 4. Mechanism scheme of the IFTDEPMG and motor.

The vibration caused by the external parallel moving gear mechanism can be balanced by increasing the number of external parallel moving gears to form a symmetrical structure. The mechanism in Figure 4 and 5 incorporates two symmetric external parallel moving gears circumferentially to greatly reduce the eccentric vibration and noise due to the crankshaft structure and improve the force-bearing conditions.

Table 1 shows the preliminary designed gear teeth and modulus. For the overlapped tooth profile phenomenon in the non-meshing zone, which is caused by the few-tooth-difference transmission, the short-teeth and long-addendum methods can be adopted[6][9]. Table 1 shows the relevant parameters.
Table 1. Gear Design Parameters.

| Parameter                        | Value | Parameter                        | Value |
|----------------------------------|-------|----------------------------------|-------|
| Gear Z1 tooth number Z₁          | 54    | Gear Z2, Z3 tooth number Z₂, Z₃  | 60    |
| Gear Z4, Z5 tooth number Z₄, Z₅  | 48    | Gear Z6 tooth number Z₆          | 18    |
| Gear Z₁, Z₂, Z₃ modulus m₁       | 2     | Gear Z₄, Z₅ modulus m₂           | 3     |
| Gear Z₁ addendum coefficient hₐ₁ | 0.72  | Gear Z₂, Z₃ addendum coefficient hₐ₂ | 0.84 |
| Gear Z₁ modification coefficient x₁ | 0.1  | Gear Z₂, Z₃ modification coefficient x₂ | 0.16 |

Then the transmission ratio is:

\[ i = \frac{Z₁}{Z₂ - Z₁} \times \frac{Z₄}{Z₆} = 24 \]  \hspace{1cm} (1)

The aforementioned few-tooth-difference transmission satisfies the following limit condition that no overlap of tooth profile interference occurs [10].

\[ Gₛ = z₁(\delta₁ + \text{inv}αₐ₁ - \text{inv}α') - z₂(\delta₂ + \text{inv}αₐ₂ - \text{inv}α') = 0, 644 > 0 \]  \hspace{1cm} (2)

where:
- \( \delta₁, \delta₂ \) — Meshing zone depth factors of Gear 1 and Gear 2; the formulas are \( \delta₁ = \arccos \frac{r²₃ - r²₁ - a²}{2a r₁} \) and \( \delta₂ = \arccos \frac{r²₃ - r²₂ + a²}{2a r₂} \);
- \( αₐ₁, αₐ₂ \) — Addendum circle pressure angle;
- \( r₁, r₂ \) — Addendum circle radius;
- \( a' \) — No-gap center distance;
- \( Gₛ \) — No-tooth contour interference limit value

4. Transmission Efficiency Bench Test of the Accelerator/Decelerator for Electromechanical Suspension

The systematic testing program tests the accelerator/decelerator bearing ability and transmission efficiency. The test parameters include input rotating speed, torque, and power as well as output rotating speed, torque, and power, which provide the basis for the efficiency calculation and performance evaluation of the accelerator/decelerator system. The test of the ADES is divided into the passive condition and the active condition.

Figure 6 shows the flowchart of the test system for testing accelerator/decelerator (here, the actual condition of the accelerator/decelerator is deceleration) in the passive condition. Figure 7 shows the actual bench.

**Figure 6.** Transmission efficiency test bench flow chart of the accelerating condition in an accelerator/decelerator for electromechanical suspension.

As shown in Figures 6 and 7, the front gear box (increasing torque with decelerator) is driven by the frequency conversion motor to drive the ADES in the passive condition. The rear gearbox decreases the
torque through acceleration and drive the magnetic powder clutch (loading) to rotate. Two torque sensors are equipped at the front of and at the rear of ADES to measure the input and output torques respectively. In this condition, the ADES is working in accelerating actually.

In the active condition, the actual condition of ADES is work in decelerating, which is similar to the test in Figure 6. The difference is the opposite installation direction of ADES, i.e. the input becomes the output, and the output becomes the input. The front and rear gearboxes should exchange to satisfy the requirements of the active decelerating condition.

**Figure 7. Transmission efficiency test of IFTDEPMG.**

Figure 8 shows the transmission efficiency curves of the active decelerating condition and passive accelerating condition.

**Figure 8. ADES efficiency curves of the active decelerating condition and passive accelerating condition.**

In Figure 8, the transmission efficiency curve of ADES shows that the maximum average efficiency of the decelerating condition is 92%, and the maximum average efficiency of the accelerating condition is 90%; thus, a high transmission efficiency is achievable. There is slight vibration and low noise (basically below 60 dB) during the entire transmission process on the bench. When the upper limit of the rear magnetic powder brake is approximately 200 Nm, the rear output torque basically reaches the loading upper limit of the bench (approximately $200 \times 10 = 2,000$ Nm) as the rear gearbox (decelerator) transmission ratio is 10 in Figure 8(a) and the transmission power is nearly 4 KW in the decelerating condition with maximum load, which proves that the accelerator/decelerator scheme for electromechanical suspension based on IFTDEPMG is feasible for small and medium tracked vehicles. We could not measure the design load condition for 8,000 Nm due to the limited testability of this bench.

5. **Conclusion**

In summary, the accelerator/decelerator designed for electromechanical suspension based on the involute few-tooth-difference planetary transmission has simple processing, high bidirectional mechanical transmission efficiency, high coincidence, good impact resistance and smooth transmission,
which satisfy the transmission requirements in active/semi-active/passive control conditions of the electromechanical suspension. It is conducive to energy recovery in electromechanical suspension in the passive or semi-active control conditions and the active control of the suspension in the active condition. Although we could not measure the design load condition of 8,000 Nm due to the limited testability, the existing bench tests show that the accelerator/decelerator scheme for electromechanical suspension based on the involute few-tooth-difference planetary transmission is feasible for small and medium tracked vehicles.

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