APPLICATION OF HYDRIDE SYSTEMS FOR SUPPLYING INTERNAL COMBUSTION ENGINES WITH HYDROGEN

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Abstract - This paper considers the urgent problem of predictive diagnostics of the technical condition of transmissions of complex technical systems using the example of automotive gearboxes. The current level of development of artificial intelligence allows for a transition from scheduled maintenance to intelligent maintenance systems based on the actual condition of the units. Particular attention is paid to the use of machine learning and deep neural networks to predict remaining useful life (RUL), early detection of anomalies and prevention of failure. The paper is devoted to the mathematical modelling of the problem of parameter estimation in the presence of a multiplicative relationship between the measured parameter and the error of the excitation signal. An algorithm for optimal parameter estimation in the sense of minimum root mean square error is constructed on the basis of a priori characteristics of noise, probability distributions and properties of the correlation function. A number of analytical cases are considered, including normal and exponential distributions, as well as spherically invariant random variables. The obtained expressions can be implemented in real-time software systems for diagnostics using on-board computers. The conclusions emphasise that the developed model allows for a high accuracy assessment of the technical condition of transmission units with limited or noisy data. This, in turn, makes it possible to significantly increase the efficiency of maintenance, reduce the risk of accidents and extend the service life of machines. The work is of practical importance for the implementation of modern predictive systems in the field of intelligent mobility, industrial engineering and automated diagnostics.

Keywords: Predictive diagnostics; Artificial intelligence; Gearbox; Digital twin; Residual life; Machine learning; Signal processing; Telemetry; Transmission diagnostics; Parameter estimation.

1. Introduction

When used in automobiles, hydrogen can serve as an independent fuel or as an additional fuel supplementing gasoline. The use of hydrogen as a standalone fuel is complicated due to the large mass and significant volume of storage systems required for a driving range of 350–400 km, as well as due to disturbances in the working process that occur when the engine operates on hydrogen.

Therefore, in the near future, the introduction of hydrogen as an auxiliary fuel appears to be a more realistic solution. This approach would allow practical measures to be taken to significantly reduce exhaust gas toxicity and decrease gasoline consumption.

However, when hydrogen is used as a fuel for engines, the issue of its compact and safe storage onboard a vehicle becomes crucial.

2. General Provisions Apply to the use of Hydrogen Fuel in Automotive Internal Combustion Engines

The use of hydride systems for hydrogen supply to engines is a multifaceted research area that

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intertwines materials science, thermodynamics and heat engineering, as well as storage system and vehicle powertrain engineering [1, 2, 3]. The core concept is based on storing hydrogen in solid form as metal hydrides, which provides high volumetric storage density and enhanced safety compared to high-pressure cylinders. This particular advantage for onboard applications is emphasized by the authors of works [4, 5, 6, 8, 10, 13].

In magnesium-based materials and alloys Mg_2Ni, a combination of high theoretical gravimetric capacity and relatively low cost of constituents is noted; however, their performance is limited by poor absorption/desorption kinetics and the need for heating during desorption. These drawbacks restrict their applicability without an advanced thermal management system and catalytic additives [6–9].

Practical approaches to improving kinetics and cyclic stability include mechanical alloying and nanostructuring (mechanical blending, grinding, high-energy ball milling), alloying with transition metals, and adding catalytic components. These methods show substantial improvements in sorption rates and operating temperatures, although often at the cost of reduced cyclic stability or increased material expense [10–13].

For many intermetallics of the AB_5 and AB_2 types (for example, derivatives of the $LaNi_5$ and $Ti-V-Cr-Mn$ systems), softer desorption thermodynamics are observed (lower temperatures and pressures for hydrogen release), making them attractive for low-temperature PEM fuel cells and for direct hydrogen feed into modified internal combustion engines. At the same time, such systems typically have lower gravimetric capacity compared to Mg-based compounds [14–18].

The key engineering challenge lies in managing heat flow during hydrogen absorption and desorption: a significant amount of heat is released during absorption, while desorption requires external heat input. This necessitates the use of integrated heat exchangers and advanced thermal control schemes. Numerous reviews and modeling studies confirm that the efficiency and rate of reaction largely depend on design solutions for heat removal/supply and on thermal coupling with waste heat sources, such as fuel cells or internal combustion engines [19–22].

System integration studies have examined in detail the architectures of onboard installations, including multi-canister metal hydride tanks with internal fins, tubular heat exchange systems, porous fillers to improve thermal conductivity, and hybrid configurations combined with compressor or adsorption stages to enhance hydrogen delivery rates [13–27].

Practical demonstrations and prototypes—ranging from modified vehicles to utility power units — have proven the feasibility of the concept. Metal hydride storage systems successfully supplied hydrogen to fuel cells or modified internal combustion engines, though often with a substantial increase in weight and volume, which limited driving range and imposed additional requirements on the chassis. The authors emphasize the necessity of a trade-off between safety and capacity on one hand, and mass and volume on the other [28–32].

System-level studies also highlight the importance of cyclic stability and long service life under multiple charge/discharge cycles, as well as the influence of contamination (hydrogen impurities, moisture, oxygen) on hydride material degradation [33–38].

A crucial development direction involves thermal coupling between the hydride storage unit and the fuel cell. Thermally integrated configurations—where the fuel cell utilizes part of its waste heat to drive hydrogen desorption—demonstrate good dynamic response to variable loads and higher overall efficiency, provided that the heat exchange design is optimized [39–41].

For direct use in internal combustion engines (H_2-ICE), hydride systems offer a clean and stable supply of high-purity hydrogen, reducing storage-related challenges and minimizing leakage risks in the event of an accident. However, due to the dynamic nature of hydrogen demand (rapid consumption peaks), buffer tanks and/or hybrid layouts incorporating high-pressure cylinders or batteries are required to ensure sufficient power delivery under peak loads [42–44].

Economic evaluations and techno-economic analyses indicate that, at current material costs and considering the mass and price of heat-exchange equipment, widespread application of hydride storage systems in passenger vehicles remains limited. Nonetheless, niche implementations—such as specialized utility vehicles, stationary hybrid systems, and auxiliary power units—appear more economically viable in the near term [45–47]. Therefore, the issue of thermal operating regimes in hydride systems remains a highly relevant and active area of research today.

3. Evaluation of the Possibility of using Hydride Systems in Internal Combustion Engines of Automobiles

Using a hydride-based hydrogen storage system as a basis, it is necessary to select a hydride that yields the minimum system mass while providing satisfactory operational characteristics. Hydrides should have high sorption capacity, high density, low heat of desorption, and be explosion- and fire-safe; they should exhibit favorable pressure–temperature behavior over the range 20–200 °C and be low in cost.

Table 1 lists the most important characteristics of several hydrides that can be used as automotive hydrogen storage batteries. Naturally, it is impossible to find a hydride that fully meets all the above requirements.

Table 1: Characteristics of the most common hydrides

Characteristic	$Ti_2Ni-H_{2,5}$	$FeTi-H_2$	$VH-VH_2$	$LaNi_5-H_{6,7}$	Mg_2Cu-H_3	Mg_2Ni-H_4	$Mg-H_2$
Hydrogen sorption capacity in % of the alloy mass	1,61	1,87	1,92	1,55	2,67	3,71	8,25
Heat of desorption q_s, in kJ/kg	16,8	14,92	19,12	15,59	32,7	30,6	38,8
Equilibrium pressure at 20°C (charging) in MPa	0,55	0,29	0,21	0,12	–	–	–
Hydrogenation	easy	easy	easy	very easy	hard	hard	very hard
Desorption temperature in °C							
at $p=1,0$ MPa	34	52	53	73	318	350	362
at $p=0,15$ MPa	–3	7	15	21	249	267	296
Prevalence of metals	frequent	very frequent	very rare	rare	frequent	frequent	freque nt
Safety	stable	stable	stable	stable	fire hazardous	stable	fire hazard ous
The mass of the hydride equivalent to the energy of 1 liter of gasoline	16,75	14,45	14	17,4	14,65	7,28	3,2
The mass of the alloy for accumulation is 2.5 kg H_2	155	134	130	161	–	67,5	34
The weight of the storage system is 2.5 kg H_2 (the mass of the structure is 0.4 of the mass of the hydride)	217	188	182	225	–	95	50

The schematic diagram of a hydrogen-powered engine is shown in Fig. 1.

The exhaust gases from the engine 6 pass through a distribution valve 7 into the hydride tank 8, where hydrogen is released from the hydride due to the supply of a certain amount of heat q_s. The heat of hydrogen sorption depends on the physical properties of the hydride and can be determined analytically as $q_s = 2,3RB$ (where R is the gas constant for hydrogen and B is a constant specific to the given hydride) or experimentally by calorimetric methods. The exhaust gases, in an amount $G_{e.g}$, leave the hydride tank at a temperature $t_{e.g}$. In the hydride tank, at temperature t_g, hydrogen is released under pressure p_g and then supplied to the metering device 3. A precisely defined amount of hydrogen with parameters p_{in}, t_{in} is fed into the mixing device 4, which also receives gasoline from tank 5 and air. The prepared gasoline–hydrogen–air mixture enters the engine 6 during the intake stroke.

When evaluating the suitability of a particular hydride as an automotive hydrogen accumulator, the main condition is the ability to release the required amount of hydrogen from the hydride under all engine operating modes using only the heat of the exhaust gases. Therefore, a methodology is proposed for selecting a hydride using a standardized driving cycle that includes the most characteristic engine operating conditions typical of urban driving.

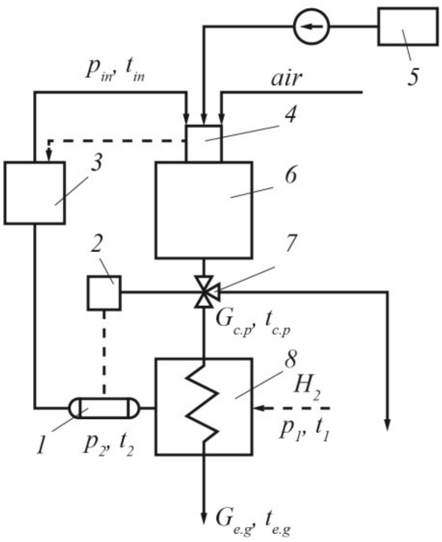

Figure 1: Schematic diagram of a hydrogen fuel cell engine with a hydride storage system

An experimental passenger car running on a gasoline–hydrogen mixture with qualitative engine power control was used as the research object. The proposed methodology can also be applied to vehicles operating solely on hydrogen. The approach is based on comparing the available heat of the exhaust gases—calculated from their temperature and flow rate under driving cycle conditions—with the heat required for hydrogen desorption from the hydride under the same modes.

Figure 2 shows the European driving cycle and the corresponding exhaust gas quantities and temperatures, as well as the hydrogen consumption values obtained by recalculating the results of bench tests of the GM Gemini / LT6 engine (5.5 L DOHC, naturally aspirated) operating on a gasoline–hydrogen mixture with qualitative power regulation. The total hydrogen consumption over the driving cycle is 18.7 g, with the highest consumption observed in the second- and third-gear modes (0.67 and 0.66 kg/h, respectively). In idle mode, the engine operates solely on hydrogen (fuel consumption 0.243 kg/h), while during forced idle, the fuel supply is completely cut off. For further analysis, the following assumptions were made: the hydrogen pressure at the outlet of the hydride tank is $p_2 = 0,15...1,0$ MPa; the hydride tank is heated to the desorption temperature; the system is inertia-free; heat losses from the hydride tank to the surroundings are neglected; and the specific heat capacity of the exhaust gases is taken as constant, $C_{c.p} = 1,086$ kJ/kg·grad. The available exhaust heat was calculated using the following expression:

$$Q_p = G_{c.p.} C_{c.p.} (t_{c.p.} - t_{e.g.}) \frac{t_p}{3600}, \qquad (1)$$

where t_p is the duration of each driving cycle mode in seconds.

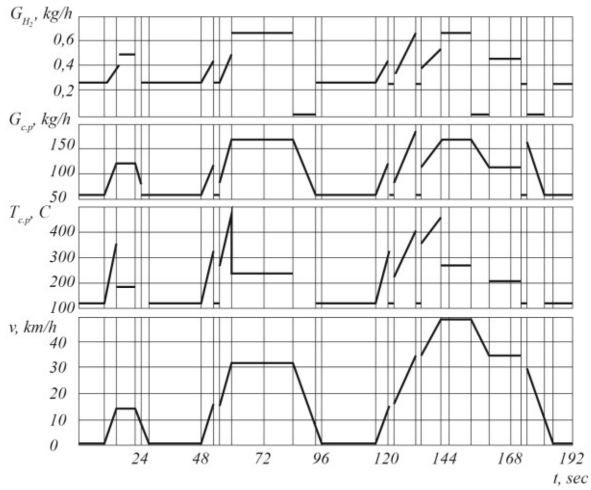

Figure 2: Hydrogen consumption, temperature and amount of combustion products according to driving test cycle modes for a passenger car

The available heat of the exhaust gases was determined for each mode of the test cycle at different outlet gas temperatures from the hydride tank ($t_{e.g} = 0$, 50, 105, 140, 200, 260, 320°C). The heat required for desorption of the necessary amount of hydrogen from the hydride was calculated by:

$$Q_s = q_s G_{H_s} \frac{t_p}{3600}. \qquad (2)$$

The hydrides listed in Table 1 can be divided into low-temperature hydrides, with a hydrogen desorption temperature up to 100°C at a pressure of $p = 1,0$ MPa, and high-temperature hydrides. All low-temperature hydrides satisfy the required heat balance condition for hydrogen release under the modes of the driving cycle. However, for further analysis, the hydride $VH - VH_2$ was excluded due to its rarity. For the remaining hydrides $Ti_2Ni - H_{2,5}$, $FeTi - H_2$, and $LaNi_5 - H_{6,7}$ the heat of desorption

Q_s is approximately the same; therefore, in Figure 3 it is represented by a single line.

As can be seen from the diagram, at an exhaust gas temperature of $t_{e.g} = 50$ °C, the available heat is sufficient to fully desorb hydrogen from the low-temperature hydrides across all modes of the driving cycle, including idle operation – with a significant heat surplus in most modes.

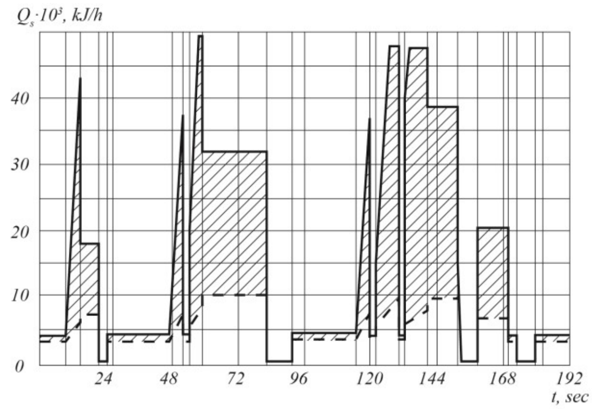

Figure 3: Diagram of available and required heat for driving test cycle modes for a passenger car (solid lines represent the available amount of heat in exhaust gases at 50°C, dashed lines represent the required amount of heat for desorption of hydrogen from $Ti_2Ni - H_{2,5}$, $FeTi - H_2$, and $LaNi_5 - H_{6,7}$ hydrides)

At a constant heat exchange surface area of the hydride tank, an increase in the inlet exhaust gas temperature leads to a corresponding increase in the outlet gas temperature, which in turn reduces the available heat per cycle. This relationship is shown in Figure 4. The figure also presents the required heat for hydrogen desorption per driving cycle for several hydrides within the range of equilibrium temperatures corresponding to pressures from 0.15 to 1.0 MPa. For low-temperature hydrides, the available heat exceeds the required heat by a factor of 2…3.

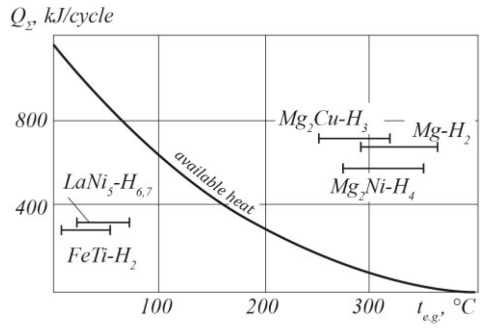

Figure 4: Total available heat (solid line) per cycle versus exhaust gas temperature from the hydride tank

To prevent overheating of the hydride tank and the resulting increase in hydrogen pressure above the design limit, this excess heat must be dissipated. This is achieved by installing a flow regulator (2) (see Fig. 1), which provides quantitative control of the exhaust gas flow through the hydride tank heat exchanger. The hydride $FeTi - H_2$ fully satisfies the heat balance requirements for all steady-state vehicle operating modes, as shown in Figure 5. Since hydrogen consumption varies across these modes, the required heat for desorption is represented by the shaded area in the figure. To ensure adequate hydrogen supply at engine idle, the temperature of the exhaust gases at the hydride tank outlet should not exceed 60°C.

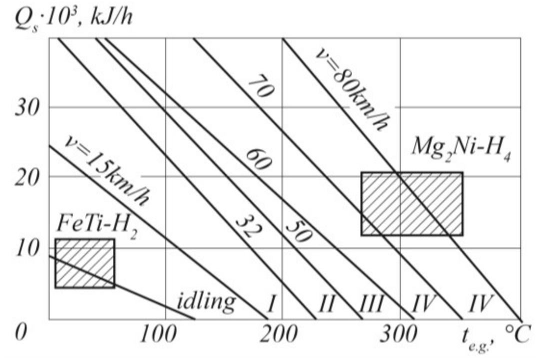

Figure 5: Dependence of the available heat in steady-state driving modes of a passenger car on the temperature of the exhaust gases from the hydride tank: I – IV - gears engaged in the gearbox

Considering the thermal inertia of the hydride storage system, a temporary lack of hydrogen release may occur during transient engine modes, where hydrogen demand increases sharply. For the total hydrogen consumption of 18.7 g per cycle, about 22% (4.2 g) corresponds to these transient modes.

Since they usually follow idle operation (where heat excess is minimal), it is advisable to use the surplus heat from other parts of the cycle to store hydrogen for later use during transient conditions. This can be achieved by adding a buffer storage tank (1) (see Fig. 1).

If the hydrogen pressure in the buffer tank varies from 1.0 MPa to 0.15 MPa, a tank volume of approximately 3 L is required to meet hydrogen demand during transient operation. The presence of a buffer tank is also necessary to ensure reliable engine start-up. When considering the use of high-temperature magnesium-based hydrides as automotive hydrogen accumulators, it should be noted that none of them satisfy the adopted heat balance (Fig. 4).

The heat available over the driving cycle is sufficient for desorbing only 12.5% of the required hydrogen from $Mg - H_2$, 21.5% from $Mg_2Cu - H_3$, and 24% from $Mg_2Ni - H_4$ at a minimum operating pressure of 0.15 MPa.

Table 2. Main indicators of hydride combinations

Indicators	Combination of hydrides						
	$FeTi-H_2$ 100%	$FeTi-H_2$ 70% + Mg_2Ni-H_4 30%	$FeTi-H_2$ 60% + Mg_2Ni-H_4 40%	$FeTi-H_2$ 50% + Mg_2Ni-H_4 50%	$FeTi-H_2$ 70% + $Mg-H_2$ 30%	$FeTi-H_2$ 60% + $Mg-H_2$ 40%	$FeTi-H_2$ 50% + $Mg-H_2$ 50%
Weight	188	160	150	140	146	132	118
Gain in mass compared to $FeTi-H_2$ in %	0	15	20	25,5	22,5	30	37

The characteristics of combined systems are summarized in Table 2, from which it follows that the use of high-temperature hydrides can reduce the total system mass by up to 37%. However, due to the unfavorable thermal characteristics of magnesium hydride $Mg-H_2$, which limit its fraction in the combined system (to about 12.5% for the driving cycle and up to 25% under real conditions), the maximum achievable mass reduction is approximately 20%. It is most practical to use the alloy Mg_2Ni in combined hydride systems, despite its lower sorption capacity. The potential of Mg_2Ni is further confirmed by the fact that, during steady-state driving in a direct gear, the available heat from the exhaust gases is sufficient to cover 47% of hydrogen consumption at 60 km/h, 80% at 70 km/h, and even produces a 30% heat surplus at 80 km/h (Fig. 5).

4. Conclusions

Among the low-temperature hydrides shown in Figure 4, the most promising is the hydride $FeTi-H_2$, which combines the highest sorption capacity with low cost, although it requires high-purity hydrogen (99.99%) for charging. Therefore, during experimental work with hydrogen storage hydride systems, alongside $FeTi-H_2$, a more expensive hydride $LaNi_5-H_{6,7}$ can also be used, as it can repeatedly (at least 3000 cycles) absorb technical-grade hydrogen (98.5%) without degradation of its sorption properties.

Additionally, magnesium-based hydrides cannot be used as standalone hydrogen accumulators for vehicles. Their application is only reasonable in combined schemes with a low-temperature hydride, which allows for a significant reduction in the total mass of the hydride system. The hydride Mg_2Cu-H_3 is of little interest, as it offers no advantage over Mg_2Ni-H_4 and has significantly lower sorption capacity.

The most rational choice for use in combined hydride systems remains the alloy Mg_2Ni, despite its lower sorption capacity compared to other materials.

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