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COMBINED OPERATION OF A DIESEL INTERNAL COMBUSTION ENGINE AND A HYDRODYNAMIC TORQUE CONVERTER IN A FORKLIFT'S POWERTRAIN

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Abstract: *The objective of this article is to derive and analyze the combined operation of an internal combustion engine (ICE) and a torque converter (TC) used in forklift transmissions. A diesel ICE model D3900K and a torque converter of type Brockhaus 1334 with cast impeller and turbine wheels, featuring a BBA blade system, were selected for the study. The external speed characteristics of the engine were determined with respect to torque and power, along with the efficiency and the dimensionless performance characteristics of the TC. The results obtained from the joint operation modeled in the MATLAB environment show that the load parabolas fully cover the engine speed characteristic from the maximum torque mode to the maximum power mode, i.e., across the engine's entire operational range.*
Keywords: *Kinematic characteristics, forklift's powertrain, internal combustion engine, torque converter.*

СЪВМЕСТНА РАБОТА НА ДИЗЕЛОВ ДВИГАТЕЛ С ВЪТРЕШНО ГОРЕНЕ И ХИДРОДИНАМИЧЕН ПРЕОБРАЗУВАТЕЛ НА ЕНЕРГИЯ В ТРАНСМИСИЯ НА МОТОКАР

ЙОРДАН СТОЯНОВ

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Резюме: *Целта на статията е да се изведат и анализира съвместната работа на двигател с вътрешно горене (ДВГ) и хидродинамичен преобразувател на енергия (ХДП), използвани в трансмисиите на мотокари. За изследването са избрани дизелов двигател модел D3900K и хидродинамичен преобразувател тип Brockhaus 1334 с ляти колела на помпата и турбината, снабдени с лопатъчна система тип BBA. Определени са външните скоростни характеристики на двигателя по отношение на въртящ момент и мощност, както и КПД и безразмерните работни характеристики на преобразувателя. Получените резултати от моделирането на съвместната работа в средата MATLAB показват, че товарните параболи напълно обхващат скоростната характеристика на двигателя — от режима на максимален въртящ момент до режима на максимална мощност, т.е. в целия работен диапазон на двигателя.*

Ключови думи: *трансмисия на мотокар, двигател с вътрешно горене, хидродинамичен преобразувател на енергия.*

1. Introduction

A large proportion of the hydrodynamic energy converters used in forklift manufacturing – specifically in their structural variant known as the hydrodynamic transformer (HT) – are complex, single-turbine units with direct transparency. These HTs allow variations in external resistances to directly influence the operation of the forklift engine, such that when the external resistances increase, the engine is loaded, and when the resistances decrease, the engine is unloaded. This characteristic enables the engine to adapt to fluctuations in external loads within the range of variation of the effective torque up to its maximum value [3].

In studying the combined operation between an internal combustion engine (ICE) and a hydrodynamic energy converter (HEC), of interest – beyond the dependencies of the output power and torque of the "ICE-HEC" assembly – are also the kinematic characteristics, which describe the relationship between the rotational speeds: specifically, n_p of the input shaft (pump wheel) and n_t of the output shaft (turbine wheel) of the HEC, as well as the dependence of these parameters on other factors, such as the transmission ratio i within the hydrodynamic converter.

These characteristics are most easily determined for a non-transparent HT, since in that case the rotational speed of the pump wheel remains constant for each load mode of the engine, independent of the rotational speed of the turbine wheel or of the corresponding resistive torque acting upon it. In all other cases, the interdependence between the rotational speeds is more complex, meaning it must be determined separately for each load mode [2].

The mathematical model for optimizing the joint operation of an "internal combustion engine – hydrodynamic energy converter" (ICE–HEC) assembly under the condition of achieving maximum output power over the widest kinematic range has been validated in the doctoral dissertation of one of the authors. The results obtained from its application in theoretical studies provide sufficient grounds to conclude that the model is suitable for such analyses, demonstrating very good convergence with experimental data [4].

Despite the availability of many simulation tools, such as MATLAB, the analytical approach (mathematical modeling) remains essential for understanding the physical interactions between the model components and validating the features of the proposed methodology in general. Therefore, this research focuses on developing the practical components of the powertrain model for future studies aimed at determining optimal control strategies. The main objective is to analyze the combined operation of an engine–torque converter (TC) system by modeling the state-space representation of the system components and ensuring adequate simulation of the forklift's automatic transmission behavior [1].

The main objective of the present work is to conduct a detailed analytical determination of the kinematic characteristics of the combined operation between a diesel internal combustion engine and a hydrodynamic energy converter under engine operating conditions.

2. Material and methods

The matching (or synchronizing) gear is a mechanical or hydrodynamic transmission stage introduced between the internal combustion engine (ICE) and the hydrodynamic torque converter (HTC) to ensure kinematic and energetic compatibility between the two subsystems.

The kinematic characteristics and the joint operation of the "ICE–HEC" system were derived and analyzed using the MATLAB development environment.

For the present study, a diesel internal combustion engine D3900K [6, 7, 8] and a torque converter of type Brockhaus 1334 with cast impeller and turbine wheels, equipped with a BBA blade system – a Bulgarian licensed production [5] – were used. The torque converter (TC) is a hydro-dynamic machine, where a turbine shaft torque is caused by the superposition of the active (impeller) and reactive (reactor) torque components. The impeller loading moment (M_I), fundamental physical expression for the pump torque , while TC is operating as a hydro-dynamic machine, can be expressed as follows [1]:

$$M_I = \rho D_a^5 \lambda_I \omega_I^2 \quad (1)$$

where ρ is density of hydro-dynamic machine's working fluid, D_a is TC active (maximum) diameter, λ_I is impeller torque coefficient, and ω_I is impeller angular speed.
Angular speed ω to pump speed n

$$M_p(n,i) = \rho D_a^5 \lambda(i) (\frac{\pi}{30})^2 n^2, \quad (2)$$

then $M_p(n,i) = \lambda(i) C n^2$. (3)

Using $k(i)$ – the torque ratio:

$$k(i) = \frac{M_t}{M_p}, \quad (4)$$

where M_t – turbine torque

-M_p – pump torque. Therefore
$M_t(n,i) = k(i) M_p(n,i) = k(i)\lambda(i) C n^2$, (5)
this gives the turbine torque for any speed ratio i and pump speed n.
Using $\eta(i)$ – converter efficiency:

$$P_t = P_p(ik(i)), \quad (6)$$

where

$$P_t = \frac{\pi}{30000} M_p n \quad (7)$$

"Fan" of load curves (joint characteristic):
For each fixed speed ratio ***i*:**

$$M_p(n) = \lambda(i) C n^2, \quad (8)$$

where $\mathbf{M_p}$ is the pump torque and **C** depends on the converter geometry. Therefore

$$f(n) = M_p(n,i) - \lambda(i) C n^2. \quad (9)$$

Combustion engine and torque converter parameters are shown in table 1 [5, 6, 7, 8].

Table 1. *Combustion engine and torque converter parameters.*

Combustion engine D3900K		
1	Torque	250 Nm / 1400 min^{-1}
2	Power	50 kW / 2400 $\min^{-1}$
Torque converter BBA1334		
1	coefficient at 75% efficiency, i_{75}	0.465
2	coefficient at 80% efficiency, i_{80}	0.54
3	coefficient at maximum torque, i_{lr}	0.445
4	maximum converter efficiency, η_{max}	0.85
5	reducer / gearbox efficiency, η_1	0.93

Imput data of torque converter are:
Relative ratio speed:

$$i = \frac{n_t}{n_p}, \quad (10)$$

where $\mathbf{n_t}$ is turbine speed;
-$\mathbf{n_p}$ – pump speed.
It indicates the operating mode of the torque converter:
-*i* = 0–0.3 → stall / start-up, maximum torque multiplication
-*i* = 0.4–0.8 → normal operating range
-*i* = 0.85–1.0 → synchronization / coupling mode

Capacity factor (flow coefficient):
This is the main pump characteristic $\lambda(i)$ by formula (8).
It describes how the pump torque increases with pump speed at a given speed ratio.
Typical behavior:
-λ rises sharply at low i (0 – 0.5);
-reaches a peak around mid-range;
-decreases as i → 1 (coupling mode).
Torque ratioby formula (4)
This function shows how much the converter multiplies torque.
Interpretation:

-k > 1 → torque multiplication (start-up, heavy load)

-k → 1 as **i → 1** → converter stops multiplying torque and acts like a hydraulic coupling.

Your data show:

-k ≈ 2.85 at i = 0 → strong torque multiplication

-k ≈ 1 at i ≥ 0.85 → end of torque-converter mode, beginning of synchronization

The external speed characteristic of the diesel engine D3900K, in terms of torque and power, is presented in Figure 2. These engines were used in forklifts and manufactured by Balkancar–Record ltd, Plovdiv.

The forklift power units exhibit the following key characteristics: a maximum developed torque of 250 Nm at an engine speed of 1400 min^{-1}, and a relatively low torque adaptability coefficient – below 1.1 [6, 7, 9].

3. Results and discussion

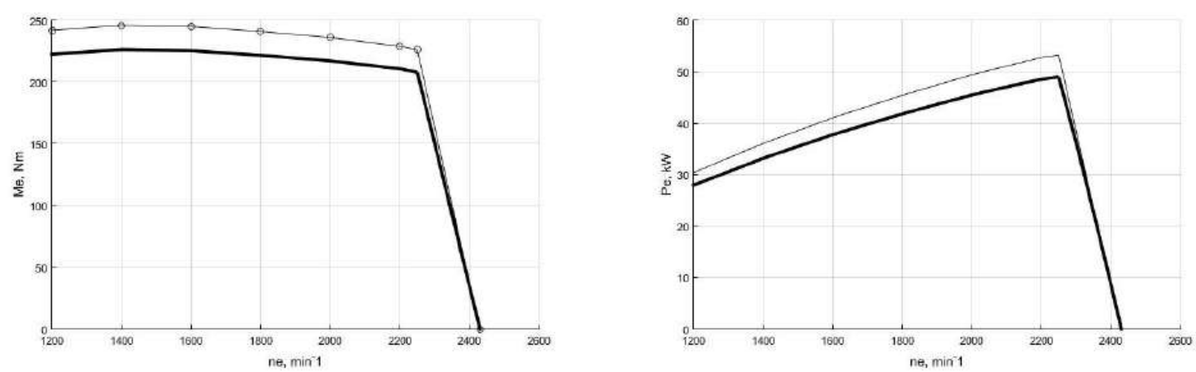
The efficiency and dimensionless performance characteristic of the hydrodynamic torque converter BBA1334 are shown in Figure 3. The torque converter has a transmission ratio of 2.9 and a maximum efficiency of 0.85 in the torque multiplication mode. The transmission ratio starts at 1.1, increases to 1.4 at a gear ratio of 0.6, and then decreases again, reaching 0.2 when the gear ratio approaches unity.

Figure 4 presents the characteristic of the combined operation of the D3900K engine with the BBA1334 hydrodynamic torque converter, assuming a direct connection between the engine crankshaft and the input shaft (pump wheel) of the torque converter. To construct the "fan" of load parabolas of the converter, determined for different fixed values of the gear ratio, the range 0…0.99 of gear ratio variation is divided into increments of 0.01.

It is assumed that the engine is equipped with a full-range governor, with the crankshaft speed varying from 1200 to 2250 min^{-1}. The non-governed operating branch of the engine (Figure 1) is divided into 15 equal intervals of 70 min^{-1} each. In this way, a total of sixteen engine load modes are formed, of which fifteen are partial load modes.

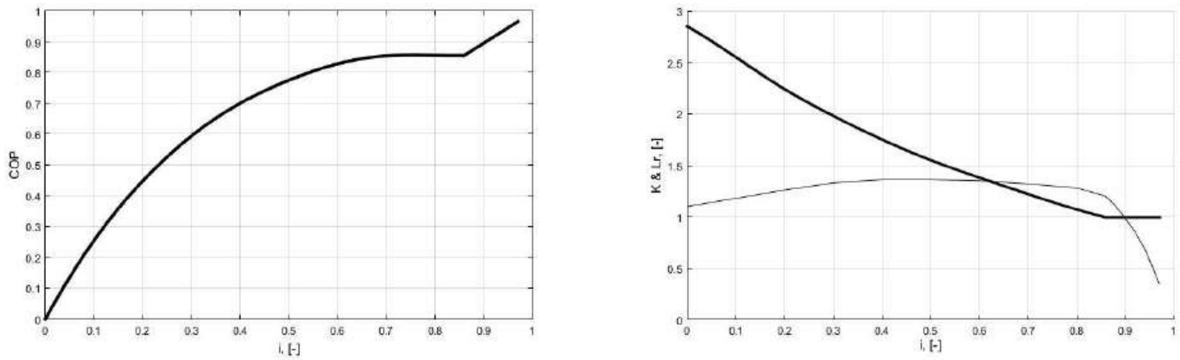
As shown in Figure 4, the "fan" of load parabolas fully covers the engine speed characteristic from the maximum torque mode to the maximum power mode, i.e., across the operational range of the engine. Only for the maximum value of the primary torque ratio (the topmost load parabola) during the first and second partial load modes (from left to right) is the torque converter unable to load the engine up to the non-governed branch.

A similar study has been conducted using mathematical models developed and implemented in the Simulink environment of MATLAB, demonstrating the modeling and optimization of the combined operation of the "ICE–HEC" assembly in a vehicle powertrain [1].



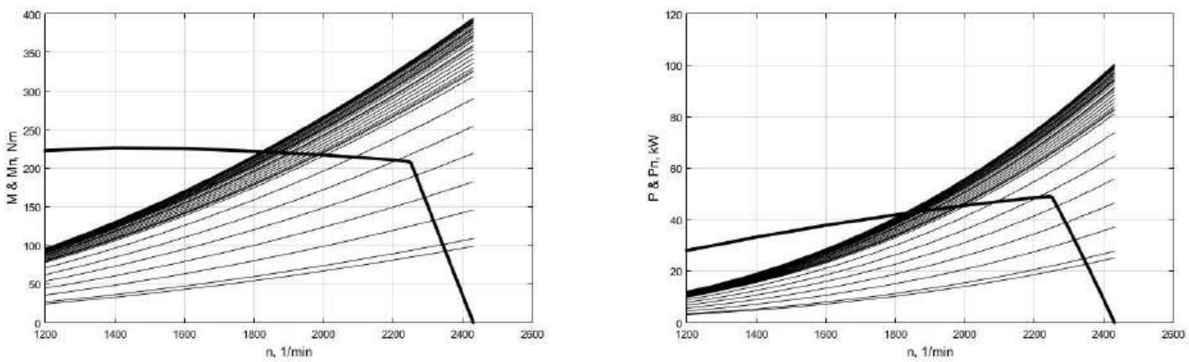
(a) (b)

Fig. 2. *Effective torque and effective power of the diesel internal combustion engine "D3900K" (Balkancar – Bulgar D3900K, licensed from Perkins).*



(a) (b)

***Fig. 3**. Efficiency and dimensionless performance characteristic of the hydrodynamic torque converter (HT).*



(a) (b)

***Fig. 4**. Characteristic of the combined operation of the diesel engine D3900K with the hydrodynamic torque converter BBA1334:*
(a) torque; (b) power.

Conclusion

The combined operation of the ICE–HEC system, developed in the MATLAB environment and tested in Automation Studio, is presented. The mathematical models described by the authors aim to optimize the operation of the "internal combustion engine – hydrodynamic energy converter" (ICE–HEC) assembly under the condition of achieving maximum output power across the widest kinematic range.

The results obtained from these theoretical investigations provide sufficient grounds to conclude that the model is suitable for conducting such studies.

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