Method for reducing the hourly fuel consumption in the transport mode of operation of a forestry machine and tractor unit

M Y Durmanov*, B G Martynov, O A Mikhaylov, S V Spiridonov

St. Petersburg State Forest Technical University, 5 Institutskiy Lane, St. Petersburg
194021, Russian Federation

*Corresponding e-mail: DurmanovMJ@yandex.ru

Abstract. By improving energy consumption in technological operations, the amount of fuel required and the operating costs of a machine-tractor unit (MTU) can also be reduced, which ultimately lowers the costs of forestry operations and reforestation. Inefficient fuel consumption significantly reduces the performance indicators of an MTU, which is also characteristic of the transport mode, although its duration is short. The article investigates the influence of a corrective device in the diesel fuel supply system on the hourly fuel consumption of a forestry MTU. For the transport mode, the diesel fuel consumption per hour is determined for dynamic loads by component: from resistance on the rise; from the MTU inertial forces; from oscillations of the MTU suspension in the longitudinal-vertical plane; from mechanical losses in the friction pairs of the engine, as well as its total value. The maximum values of the total dynamic component of the hourly fuel consumption in the transport mode are observed at frequencies close to 2.5 s⁻¹, i.e. its own, energy-consuming frequency of oscillations of the rotational speed of the crankshaft of an SMD-20T.04 engine. To improve the fuel efficiency of an MTU diesel engine, it is necessary to introduce a corrective device into the design of the high-pressure fuel pump (HPFP). As a corrective device, it is advisable to use an oscillation damper of the rail of the fuel pump (FPR).

1. Introduction

Minimizing the amount of energy required to carry out technological operations reduces the amount of fuel required and the operating costs of a machine-tractor unit (MTU) [1, 2], which ultimately reduces the costs of forestry operations and reforestation. Inefficient fuel consumption significantly reduces the performance indicators of an MTU, which is also characteristic of the transport regime, although its duration is short [3-6].

It is known [1, 2, 7] that each type of engine and its system for controlling the speed and fuel supply have their own frequencies. For the diesel engines SMD-18BN and SMD-20T.04 at values of natural frequencies close to 2.51 s⁻¹, the greatest deviations of the fuel pump rail (FPR) from the average set values have been observed.

Studies of the effect of the high pressure fuel pump (HPFP) of the LSTN-49010 type of the SMD-18BN diesel engine on the quality of the fuel supply showed [8] that, when the fuel is cut off, a hydrodynamic force arises with an amplitude at a frequency of 2.51 s⁻¹, which turns the plunger and associated FPR in the direction of reducing the magnitude of the cyclic feed and turns off the speed controller (SC). The speed controller, trying to restore the given mode, returns the FPR to its original
position with an overshoot, accompanied by an increased cyclic feed, and as a result, by an increase in the amplitude of the oscillations of the crankshaft rotation speed (figure 1) and a decrease in the constant component of the rotational speed.

Of the four natural frequencies of the amplitude-frequency characteristic (AFC) of the hydrodynamic force of the HPFP, only one \( \omega_1 = 2.5 \text{ s}^{-1} \) coincides with the amplitude-frequency characteristic of the SC [8], being an additional source of excitation, enhancing the oscillatory process in the system “HPFP - speed regulator”, and creating conditions under which precise dosing of the cyclic feed and the beginning of fuel injection are impossible.

In order to reduce the amplitude of the rail vibrations and the negative effect of the hydrodynamic force on the quality of the speed control process, an oscillation damper has been developed [9]. Figure 1 shows the frequency characteristics of the FPR and the rotational speed of the SMD-18BN drive with and without an FPR oscillation damper. Figure 2 shows an HPFP of the LSTN-49010 type with an FPR oscillation damper mounted on a test bench [8].

The purpose of the work is to confirm the efficiency of using an FPR oscillation damper to reduce the hourly fuel consumption of the SMD-20T.04 diesel during the transport [10] and arable [11] modes of operation of a forestry MTU. The proposed method for increasing the operational efficiency of an MTU, especially relevant at the stage of tractor design, serves to improve the quality of design and engineering work, and to improve the design of a forestry MTU [12, 13].

### 2. Methods and Materials

A model of a forestry MTU functioning in the transport mode was implemented in the MathCAD mathematical environment, and the Microsoft Office Excel application was used to process the results of calculations and for graph-building. The calculation method is described below.

The main external influences in the model were: the surface profile of the felled area, defined by the correlation function and spectral density, frequency of load oscillations on the tractor’s sprockets, and speed of the MTU. The unsteady nature of forces of resistance to the motion of the MTU,
described by an ergodic stationary random process, is modelled for the entire frequency spectrum of the input load moment. The article discusses the transport mode of operation of an LHT-100 tractor with a PKL-70 plow. For the MTU under consideration, a sufficient amount of operational indicators has been accumulated, which are necessary for estimating modelling errors, since it has been widely used in forestry and reforestation operations.

Figure 2. The high-pressure fuel pump (HPFP) of type LSTN-49010 with an FPR oscillation damper and sensors mounted on a test bench: 1 - the FPR oscillation damper; 2 – the FPR displacement sensor; 3 - the camshaft speed sensor of the HPFP.

2.1. Analytical expressions for determining the hourly fuel consumption of an MTU diesel engine in the transport mode

The expression for the hourly fuel consumption of an MTU diesel engine in the transport mode has two components - regular $B_0^t$ and variable $B^t(\omega, \nu_0)$, written in the operator form (at $s = j\omega$) [2, 10]:

$$B_0^t = E_i n_0 \left[ \frac{R}{i_t \eta_m} A_i^t + D_t (a_i + b_i n_0) \right];$$

$$B^t(\omega, \nu_0) = E_i M_a^a \omega \cdot |U_{11}(j\omega, \nu_0)| \cdot \left\{ \frac{R}{i_t \eta_m} \left[ A_i^t + 2A_4 \omega \cdot |U_{11}(j\omega, \nu_0)| + 2f_{ir} \right] \right\}^{\theta_i^t(j\omega, \nu_0)}$$

$$+ D_t \left[ \frac{a_i}{P_m^m} \left( \frac{4\omega^2 + \gamma^2}{\omega^2 + \gamma^2} \right)^{0.5} \cdot |G_{01}(j\omega, \nu_0)| + 2\eta_1 \omega \cdot |U_{11}(j\omega, \nu_0)| \right];$$

where, $E_i = \frac{3.6\pi}{30\eta_1 H_n}$; $A_i^t = mg(\sin \alpha + f_{ir} \cos \alpha)$; $D_t = \frac{V_{je}}{\pi \tau_e}$; $A_4 = \frac{\pi R}{30i_t} m$,

where, $n_0 = 0.8n_n$; $n_1$ - the nominal speed of the diesel crankshaft; $R$ - the radius of the leading sprockets; $i_t$ - the transmission ratio; $\eta_m$ - the mechanical efficiency, $\eta_m = \eta_1 \cdot \eta_{mov}$; $\eta_1$, $\eta_{mov}$ - the efficiency of the transmission and propulsion, respectively; $a_i$, $b_i$ - the coefficients obtained
experimentally for each type of engine; $M^*_{m}$ - the amplitude value of the input disturbance; $M^*_{n}$ - the nominal effective torque; $\omega$ - the angular speed of rotation of the crankshaft; $U_{11}(j\omega)$ - the transfer function of the rotational speed of the crankshaft of the MTU power unit; $q_0$ - the MTU movement speed; $m$ - the mass of the MTU, $m = m_t + m_{pl};$ $m_t,$ - the mass of the tractor; $m_{pl}$ - the mass of the plow; $\alpha$ - the angle of the elevation of the track; $f_{rf}$ - the coefficient of friction of the rolling propulsion; $\Theta_1^i(j\omega)$ - the transfer function of the oscillations of the MTU frame in the longitudinal-vertical plane in the transport mode; $P_{in}$ - the oil pressure in the main oil line (MOL) at nominal rotation speed; $\gamma = 10^{-3};$ $\omega_N$ - the nominal angular speed of rotation of the crankshaft. $G_01(j\omega)$ - the transfer function of oil pressure in the MOL; $\eta_i$ - the indicator engine efficiency; $H_u$ - the lowest calorific value of fuel; $V_c$ - the working volume of one engine cylinder; $i$, $r_\tau$ - the number of cylinders and the engine cycle, respectively.

The transfer function of the rotational speed of the crankshaft of the MTU power unit in a disturbing action (with a fixed position of the body $h(t)$ that sets the value of the cyclic fuel supply: $h_0 = \text{const})$ [1, 2]:

$$U_{11}(j\omega) = \frac{k_{\xi1}(T_2^2s^2 + 2T_2\xi,s + 1)}{(T,s + 1)(T_3^2s^2 + 2T_3\xi_2,s + 1)(T,s + 1)},$$

where, $k_{\xi1}$ - the transmission speed ratio; $T_1, T_2, T_3, T_4$ - the time constants; $\xi_1$, $\xi_2$ - the attenuation coefficients.

For the engine SMD-20T.04: $k_{\xi1} = 1.80; T_1 = 1.073 s; T_2 = 0.531 s; T_3 = 0.398 s; T_4 = 0.354 s; \xi_1 = 0.300; \xi_2 = 0.250$ [1, 2].

The input impacts for the MTU from the side of the felling are unevenness of the micro-relief and heterogeneity of the soil which are the cause of fluctuations $F_r(t)$ in the resistance forces on the leading sprockets.

Note that for the MTU, taking into account its mass $m$, the moment of inertia given to the crankshaft $I_a$ and the time constant $T_1$ are

$$I_a = I_e + \frac{mr^2}{l^2}; T_1 = \frac{\pi}{50} \frac{n_n^2}{N_n},$$

where, $I_e$ - the moment of inertia of the engine; $N_n$ - rated engine power.

The transfer function of the oil pressure in the engine MOL [1, 2]:

$$G_{01}(j\omega) = k_{m1} s \cdot U_{11}(j\omega),$$

where, $k_{m1}$ - the transfer rate of oil pressure in MOL: $k_{m1} = 1.20.$

The transfer function of the oscillations of the MTU frame in the longitudinal-vertical plane in the transport mode was obtained theoretically [2, 6, 10]:

$$\Theta_1^i(j\omega) = \frac{c_1z_{mr} \omega^3 \cdot (m^2(c_1 - m_z \omega^2)^2 + (m_z \beta_1 \omega^2)^2) \cdot \left[(m_z \omega^4 - (c_1m_z + \beta_1^2) \omega^2 + c_1^2)^2 + [\beta_1\omega(2c_1 - m_z \omega^2)]^2\right]^{0.5}}{[m_z \omega^4 - (c_1m_z + \beta_1^2) \omega^2 + c_1^2]^2}.$$
\[ m'_z = m_{10} + m_{20}; \quad m''_z = m_0 k_1 + m_2 k_2; \quad m_z = m_1 + m_2; \quad m_{10} = m_1 + m_0; \quad m_{20} = m_2 + m_0; \]

\[
k_1 = \left( \frac{m_1}{m_0} \right)^2 + 1 - \frac{2m_0 \cos 0.39}{m_0}; \quad k_2 = \left( \frac{m_0}{m_2} \right)^2 + 1 - \frac{2m_2 \cos 0.39}{m_2};
\]

\[
\beta_1 = 2 \nu_n \sqrt{c_m}; \quad m_1 = \frac{I_s + (m_{ns} + m_{pl}) l_2^2}{l^2}; \quad m_2 = \frac{I_s + (m_{ns} + m_{pl}) l_2^2}{l^2};
\]

\[
m_0 = \frac{I_s - (m_{ns} + m_{pl}) l_1 l_2}{l^2}; \quad m_\lambda = m_1 m_2 - m_0^2 \mu_\lambda; \quad \mu_\lambda = 1 - \frac{m_0^2}{m_1 m_2};
\]

\[
\nu_n = 0.1; \quad m_{ns} - \text{the sprung mass of the tractor with a plow}; \quad m_{ns} = 8400 \text{ kg}; \quad l_1 = 0.65 \text{ m}; \quad l_2 = 1.10 \text{ m}; \quad l - \text{distance between the axes of the carriages of the tracked mover}; \quad l = l_1 + l_2 = 1.75 \text{ m}; \quad I_s - \text{the moment of inertia of the system}; \quad I_s = 26154 \text{ kg} \cdot \text{m}^2 [2, 6, 10].
\]

By substituting in (2) the values of \( U_{11} (j \omega) \) from (3), \( G_0 (j \omega) \) from (5), and \( \Theta_1 (j \omega) \) from (6), we determine the surface of the state of the frequency characteristics (FC) of the hourly fuel consumption of the MTU diesel engine in the transport mode (figure 3). The numerical values of the hourly fuel consumption are determined by substituting the following source data in (1) and (2):

\[
V_c = 1.575 \text{ l}; \quad \epsilon = 4; \quad \tau_c = 2; \quad a_i = 0.45; \quad b_i = 0.97 \times 10^{-3}; \quad \eta_i = 0.40; \quad H_u = 41300 \text{ kJ/kg}; \quad P_{mn} = 0.6 \text{ MPa}; \quad n_n = 1900 \text{ min}^{-1}; \quad N_en = 88 \text{ kW}; \quad I_c = 2.40 \text{ kg} \cdot \text{m}^2; \quad M_en = 480 \text{ N-m}; \quad \gamma = 0.188 \text{ s}^{-1}; \quad F_y = 0.15 M_en; \quad \eta_m = 0.68; \quad R = 0.238 \text{ m}; \quad m_i = 10400 \text{ kg}; \quad m_{pl} = 520 \text{ kg}; \quad f_0 = 0.15; \quad z_m = 0.06 \text{ m}; \quad \alpha = 5^\circ [2, 6, 10].
\]

**Figure 3.** The state surfaces of the FC of the hourly fuel consumption of the MTU diesel engine based on the LHT-100 tractor with the PKL-70 plow in the transport mode depending on the speed of movement, with the standard suspension stiffness \( c_1 = 1400 \text{ kN/m} \): (a) - with a standard diesel engine; (b) - with an oscillation damper of the FPR.

Performing sections in a longitudinal-vertical plane (figures 4 and 5) for any fixed value of the regular speed \( \nu_0 \) of movement of the MTU and over the entire range of frequencies \( \omega \) of oscillations of the load on the leading sprockets, one can calculate the regular component \( B'_0 \) and the dynamic component of the hourly fuel consumption \( B'(\omega, \nu_0) \) in the transport mode.
Figure 4. Frequency response of the hourly fuel consumption by components in the MTU transport mode based on the LHT-100 tractor with the PKL-70 plow with the suspension stiffness $c_1 = 1400$ kN/m and travel speed $v_0 = 1.15$ m/s (III gear): (a) - with a standard diesel engine; (b) - with an oscillation damper of the FPR; 1 - resistance to the movement of the MTU on the rise; 2 - MTU inertial forces; 3 - tractor oscillations in the longitudinal-vertical plane; 4 - mechanical losses in the engine friction pairs; 5 - the total consumption for dynamic loads.

Figure 5. Frequency response of the hourly fuel consumption by components in the MTU transport mode based on the LHT-100 tractor with the PKL-70 plow with suspension stiffness $c_1 = 1400$ kN/m and travel speed $v_0 = 1.78$ m/s (IV gear): (a) - with a standard diesel engine; (b) - with an oscillation damper of the FPR; the legend as in figure 4.

2.2. Analysis of the hourly fuel consumption components of the MTU diesel engine in the transport mode

Using formula (2), the losses of the hourly fuel consumption per dynamic load for each component in the frequency spectrum $0 \ldots 20$ s$^{-1}$ were calculated, as well as the total for different values $c_1 = 1800; 1400; 1000$ kN/m:

1 - from the resistance on the rise at an angle $\alpha = 5^\circ$

$$B_1^i(\omega) = \frac{E_i R M^a_e}{i\eta_m \omega_e} A_1 \cdot \int_{\omega=0}^{\omega=20} \omega U_{11}^i(j \omega) \, d\omega; \quad (7)$$

2 - from the inertial forces of the MTU

$$B_2^i(\omega) = \frac{2E_i R M^a_e}{i\eta_m \omega_e} A_4 \cdot \int_{\omega=0}^{\omega=20} \omega^2 U_{11}^i(j \omega) \, d\omega; \quad (8)$$
3. Results and Discussion

Despite a short duration of the transport mode of a forestry MTU, it is relatively energy-intensive and is characterized by a high hourly fuel consumption. In the transport mode, the frequency response of the MTU hourly fuel consumption for dynamic loads is realized with two extremes (figures 4 and 5, curves 5). The highest consumption occurs in the range of natural frequencies of oscillations of the engine rotation speed $\omega_{le}=2.23 \ldots 2.88 \text{ s}^{-1}$. In terms of the structure of the dynamic component, the components of resistance to the movement of the MTU on the rise and oscillations of the tractor in the longitudinal-vertical plane have the highest values of fuel consumption (figures 4 and 5, curves 1 and 3).

The speed of movement $\nu_{0}$ has a significant impact on the size of the regular component of fuel consumption per hour $B'_{0}$, as well as on the elements of the dynamic component $B'_{1}(\omega)$ (table 1), therefore the choice of the transmission ratio of the transmission and gearbox at the design stage should provide effective traction and speed modes of the MTU.

To improve the fuel efficiency of the MTU diesel engines, the design of which includes the fuel pump rail (FPR), it is necessary to use a corrective device. As a corrective device, it is advisable to use an FPR oscillation damper [2, 8, 9, 10]. The oscillation damper is used to reduce the amplitude of oscillations of the rail and the negative effect of the hydrodynamic force on the quality of the speed control process. The damping properties of the oscillation damper can reduce the effect of hydrodynamic forces during fuel cut-off, and also provide resistance when the FPR moves towards an increase in the cyclic fuel supply.
Table 1. Calculation results of the hourly MTU fuel consumption based on the LHT-100 tractor with the PKL-70 plow in the transport mode. In the numerator - with a standard diesel engine, in the denominator - with an oscillation damper of the FPR.

| MTU speed \( \upsilon_0 \), m/s | Regular component \( B_0^1 \), kg/h | Total dynamic component \( B^1(\omega) \), kg/h with different stiffness \( c_i \), kN/m | Components the dynamic component \( B^1(\omega) \), kg/h with stiffness \( c_i = 1400 \) kN/m |
|---------------------------------|-----------------------------------|----------------------------------|-----------------------------------|
| \( \upsilon_0 \)               | \( B_0^1 \)                        | \( B(\omega) \)                    | \( B(\omega) \)                    |
| \( \upsilon_0 \)               | \( B_0^1 \)                        | \( B(\omega) \)                    | \( B(\omega) \)                    |
| 8.6a                           | 6.983                             | 1.135                             | \( 0.616 \)                        |
|                                |                                   | 0.853                             | \( 0.025 \)                        |
| 1.15b                          | 9.337                             | 1.414                             | \( 0.413 \)                        |
|                                |                                   | 1.461                             | \( 0.004 \)                        |
| 1.78c                          | 14.453                            | 1.765                             | \( 0.455 \)                        |
|                                |                                   | 1.821                             | \( 0.019 \)                        |
|                                |                                   | 1.802                             | \( 1.802 \)                        |
|                                |                                   | 1.320                             | \( 0.711 \)                        |
| 1.280                          | 1.337                             | \( 0.606 \)                        | \( 0.711 \)                        |
| \( \omega_0 \) = 2.23 s\(^{-1} \) – II gear (\( i_t = 44.226 \)); |                                   | \( 0.711 \)                        | \( 0.016 \)                        |
| \( \omega_0 \) = 2.51 s\(^{-1} \) – III gear (\( i_t = 32.854 \)); |                                   | \( 0.711 \)                        | \( 0.016 \)                        |
| \( \omega_0 \) = 2.88 s\(^{-1} \) – IV gear (\( i_t = 21.271 \)); |                                   | \( 0.711 \)                        | \( 0.016 \)                        |

\( \omega_0 \) - Components: 1 - resistance to the movement of the MTU on the rise; 2 - inertial forces of the MTU; 3 - tractor oscillations in the longitudinal-vertical plane; 4 - mechanical losses in the friction pairs of the engine.

Acknowledgments
The authors express their deep gratitude to Associate Prof. V P Antipin for his invaluable assistance with the manuscript.

References
[1] Antipin V P 2012 Power consumption of a machine-tractor unit (St Petersburg: Publishing House of The Polytechnic University)
[2] Antipin V P 2017 Productivity, energy consumption and resource of the machine-tractor unit (St Petersburg: Publishing House of The Polytechnic University)
[3] Antipin V P, Durmanov M Y and Mikhaylov O A 2019 Choosing Transmission Gearset for Agricultural Aggregates Based on Energy Consumption Proc. of the 4th Int. Conf. on Industrial Engineering, ICIE 2018 ed A Radionov et al. (Springer, Cham) pp 1591–1600
[4] Durmanov M Y, Martynov B G and Spiridonov S V 2019 Energy and Fuel Consumption of an Agricultural Aggregate Proc. of the 4th Int. Conf. on Industrial Engineering, ICIE 2018 ed A Radionov et al. (Springer, Cham) pp 1601–1612
[5] Vlasov E N, Mikhailov O A, Durmanov M Y and Epifanova A Yu 2015 Estimating the amount of energy spent on the implementation of the tangential power of the tractor LHT-100 in the plowing mode Izvestia Sankt-Peterburgskoj lesotehniceskoj akademii (St Petersburg: SPbGLTU) 212 pp 104–112
[6] Vlasov E N, Mikhailov O A, Durmanov M Y and Epifanova A Yu 2015 Estimating the amount of energy spent on the implementation of the tangential power of the tractor LHT-100 in the transport mode Izvestia Sankt-Peterburgskoj lesotehniceskoj akademii (St Petersburg: SPbGLTU) 213 pp 138–147
[7] Krutov V I 1978 Internal combustion engine as an adjustable object (Moscow: Mechanical Engineering) 472 p
[8] Shevtsov A A 1987 Improving the fuel economy of skidders on transient operating modes, Candidate of Tech. Sciences thesis, Leningrad, 182 p
[9] Antipin V P, Gribov S A, Shevtsov A A, Kozlov A V and Crystal M E 1986 *Direct-effect speed controller for internal combustion engines* [In Russian - *Regulyator skorosti pryamogo deystviya dvigatelya vnutrennego sgoraniya*] Certificate 1276843 (15 December 1986) Bulletin 46

[10] Durmanov M Y, Kulikov V N and Mikhailov O A 2019 The influence of the parameters of a forestry machine and tractor unit on the hourly consumption of diesel fuel in the transport mode *Proc. of Scientific and Technical Conf. of the Institute of Technological Machines and Forest Transport based on the results of research work in 2018* (Electronic resource) ed V A Sokolova (St. Petersburg: SPbGLTU) pp 110–120

[11] Martynov B G, Spiridonov S V and Durmanov M Y 2019 Influence of the parameters of a forestry machine-tractor unit on the hourly fuel consumption of a diesel engine *IOP Conf. Series: Earth and Environmental Science* (IOP Publishing) 316 012035

[12] Spiridonov S V, Durmanov M Y and Mikhailov O A 2017 Energy costs for the implementation of the tangential force of the forestry MTU in the transport mode *2nd Int. Scientific and Technical Conf. “Forests of Russia: politics, industry, science, education”* (St Petersburg: SPbGLTU) vol 3 pp 43–46

[13] Durmanov M Y, Spiridonov S V and Mikhailov O A 2018 Estimated hourly fuel consumption of a forestry machine-tractor unit at the design stage *3rd Int. Scientific and Technical Conf. “Forests of Russia: politics, industry, science, education”* (St Petersburg: SPbGLTU) vol 2 pp 164–167