MODERNIZATION OF FANS OF DIESEL LOCOMOTIVES COOLING SYSTEM

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ABSTRACT

The article introduces a technical solution for modernization of a fan of cooling system of locomotive diesels. The new patented design eliminates imbalance of the fan wheel and increases its reliability during operation. The authors set out operation principle of the device and method to determine a number of rolling elements that perform a function of imbalance loads. The proposed development is the result of cooperation between research departments of MIIT and Yelets University.

Keywords: locomotive, diesel, cooling system, fan wheel, imbalance, modernization.

Background. *Compliance with normal temperature in the cooling system of diesel engines affects reliable operation of locomotives [1–3].*

Blade fan wheels of cooling system of diesel of locomotives have different types of drives, they are mechanical, hydraulic or electric. Given substantial rotation speeds of fan wheel (1000 rev / min), strict requirements are imposed on the quality of balancing. Nevertheless, during operation a steady imbalance caused by operating conditions is often observed.

The article considers a new design of the fan wheel, ensuring reliability of its operation (Pic. 1).

Objective. *The objective of the authors is to consider possible modernization of fans used in cooling systems of diesel locomotives.*

Methods. *The authors use general scientific and engineering methods, comparative analysis, evaluation approach, modeling, mathematical apparatus.*

Results. *Fan wheels of cooling system of diesels of locomotives of TEP70 type have an outer diameter of 1600 mm and rotate at a frequency of 1380 rev / min [1–3]. Pic. 2 shows wheel design, blades of which are made by stamping of 2 mm thick sheet steel. Blades 1 are welded to hub 3 and stiffness flanges 2, which increase strength of their attachment. A spinner 4 is attached to the upper part of the hub.*

Sometimes during operation cracks appear at the points, where blades are fixed. That is due to vibration caused by imbalance. The analysis showed that the size of cracks is 6 mm. To prevent this type of defect, bladed wheels are subjected to a mandatory balancing, an imbalance is eliminated with welding of balancing weights [4, 5].

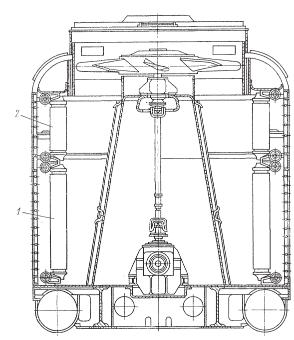
In this regard, following the study of national and foreign patents RU204783 C1 of 10.11.1995, RU119808 U1 of 27.08.2012, US0006349125 B2 of 05.02.2002, WO 2008083255 A1 of 10.07.2008 and bibliographic sources a solution was developed at the level of the invention [6], precluding an imbalance of the fan wheel and appearance of cracks in welding of wheel blades.

The proposed option (Pic. 3) is a result of creative collaboration of the department of «Trains and Locomotives» of Moscow State University of Railway Engineering and the department of «Mechanical Engineering» of Yelets State University.

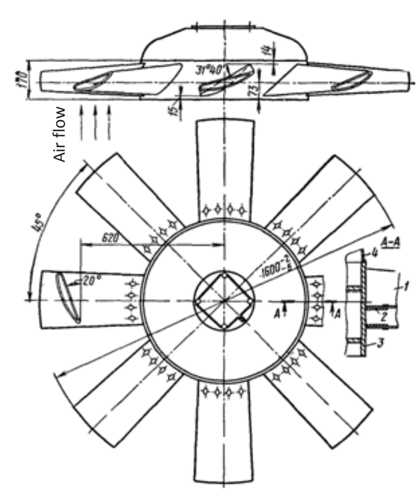
Wheel comprises a drum 1, blades 2 and stiffening plates 3. A hollow ring 5 is rigidly secured by plates 4 to blades. Ball shaped rolling elements 6 are movably arranged in the hollow ring.

At rest rolling elements 6 are located (whether grouped or isolated) in any part of the hollow ring 5 of the fan wheel. When the drive operates blade, wheel rotates clockwise W. Rolling elements 6 with the increasing angular velocity ω_κ have lower speed ω_{in} due to the fact that they are exposed to inertial forces P_i, the forces of its own weight P_G and forces of parasitic resistance P_{PR}. At the same time rolling elements 6 are exposed to driving force P_D acting in the direction of rotation of the fan wheel, resulting from the presence of friction forces between rolling elements and the inner surface of a hollow ring.

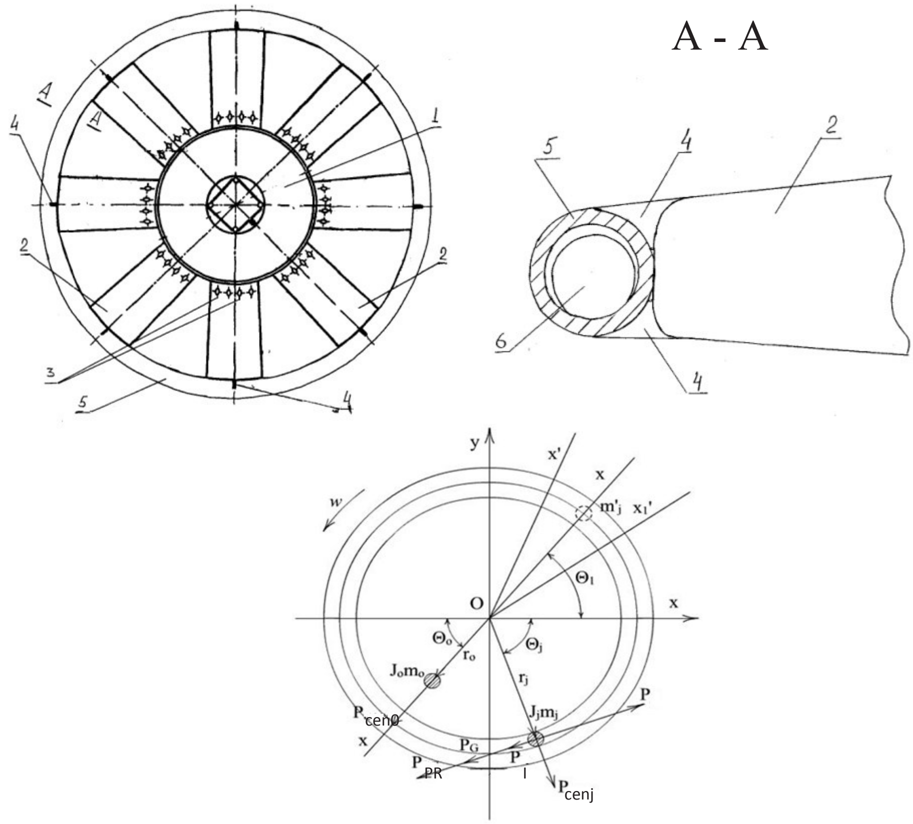
In the presence of the fan wheel imbalance Δ_1, emerging from the unbalanced mass m_1, there is a centrifugal force P_{cen} defined as $P_{cen1} = m_1 \rho \omega_\rho^2$, where $m_1 \rho = \Delta_1$. Simultaneously, rolling elements 6 (on the calculated scheme in Pic. 3 for simplicity one rolling element is shown) will be subject to centrifugal inertial force $P_{cen} = m_{in} r \omega_r^2$, where $m_{in} r = \Delta_2$. Thus Δ_2 is dynamic



Pic. 1. Mine of locomotive cooling apparatus.



Pic. 2. Fan wheel.



Pic. 3. Fan wheel – top view, section across A-A, design scheme.

counterweight. It is known that the balancing of mass m_{in} happens when this mass will take a position in the plane XX, passing through the rotation center of the wheel O and center of gravity of unbalanced mass m_1, or in the plane OX '(OX_1'), arranged to it at an angle α, which determines the position of the dynamic counterweight Δ_2 and depends on the difference between masses m_1 and m_{in}. In case of change of the fan wheel rotation angle α is automatically adjusted so that it will provide reliable wheel balancing [7].

Let's consider rotating wheel, which has a concentrated mass m_0, causing its imbalance, and freely moving rolling elements with own mass m_j, located in the hollow ring, fixed to the ends of the blades of the fan wheel (Pic. 3). It is known that the balancing of mass m_0 happens when the masses m_j will occupy the position in the plane XX, passing through the rotation center of the wheel O and the center of gravity of the unbalanced mass m_0, or in the plane OX' (OX_1'), arranged to it at a certain angle, determining position of dynamic counterweight and depending on the difference between masses m_0 and m_j. If the wheel speed changes this angle will be adjusted automatically, thereby providing a reliable balancing of rotating blade wheel.

The equation of wheel motion in accordance with the design scheme (Pic. 3) contains the values that are identified as:

θ_j – angular deflection of j rolling elements from the axis OX, rad;

r_j –radius of position of rolling elements with respect to the wheel center of rotation, m;

m_j – own mass of rolling elements, kg;

ω – angular wheel speed, s^{-1};

m_0 – own imbalance mass, kg;

r_0 – radius of imbalance position relative to wheel rotation center, m;

θ_0 – angular deviation of imbalance from axis OX, rad;

J_0 – moment of inertia of the wheel, taking into account the imbalance m_0, $kg \cdot s^2 \cdot m$;

m_r – total mass of wheels and rails with rolling elements, kg;

J_k – moment of inertia of the wheel and rails with rolling elements, $kg \cdot s^2 \cdot m$;

P_D – driving force applied to rolling elements, N;

P_I – inertial force of resistance, N;

P_G – resistance force of its own weight of rolling elements, N;

P_{PR} – force of parasitic resistance to movement of rolling elements, N;

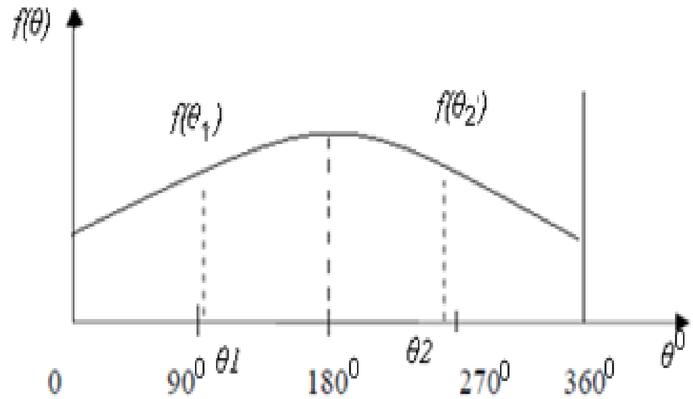
$Pcen_j$ – centrifugal force of inertia, N;

$Pcen_0$ – centrifugal force caused by imbalance of the wheel, N.

As an example of the system of generalized coordinates we take functions x_k, y_k and angular deviation of imbalance from the axis OX θ_0. Let's consider a finite number n of natural vibrational modes and introduce notations:

$$x = \{x_1(t), x_2(t), \ldots, x_n(t)\}^T, \; y = \{y_1(t), y_2(t), \ldots, y_n(t)\}^T.$$

Let's consider the case of uniform rotation of the wheel in the horizontal plane. Let's turn to complex variables and introduce the vector z = x + iy (where x – real part of the complex number, and y – imaginary). Denoting via $\overline{\mathbf{z}}$ vector, which is complexly conjugated to z, the kinetic energy of the system can be written as:



Pic.4. Graph of angle functions.

$$T=\frac{1}{2}z^{-T}\left(m_{\kappa}+J_{\kappa}+\left(m_{\kappa}+m_{0}\right)\right)\dot{z}+\frac{1}{2}\left(J_{0}+m_{0}r_{0}^{2}\right)\dot{\theta}_{0}^{2}-$$
$$-J_{0}\dot{\theta}_{0}Im[z^{-T}z]+m_{0}r_{0}\dot{\theta}_{0}Im\left[\dot{z}^{T}e^{-i\theta_{0}}\right]. \qquad (1)$$

At the same time, assuming that rolling elements in an amount of N are material points, we take as generalized coordinates components of the speed vector z and rotation angles for each of them θ_j, $j = 0…N$. Expressions of kinetic T and potential energy U can be written in the form.

$$T=\frac{1}{2}\begin{pmatrix} z^{-T}(m_{\kappa}+J_{\kappa}+\sum_{j=0}^{N}m_{j})\dot{z}+J_{0}\,\dot{\theta}_{0}^{2}+\sum_{j=0}^{N}m_{j}r_{j}^{2}\theta_{j}^{2}- \\ -2J_{0}\,\dot{\theta}_{0}\,Im\left[z^{-T}z\right]+\sum_{j=1}^{N}2r_{j}m_{j}\dot{\theta}_{j}Im\left[\dot{z}^{T}e^{-i\theta_{j}}\right] \end{pmatrix}; \qquad (2)$$

$$\mathrm{U}=\frac{1}{2}m_{\kappa}z^{-T}z. \qquad (3)$$

Using expressions (1) and (3), we write Lagrange equation of the 2nd kind for the system without rolling elements:

$$\begin{cases} \left(\mathrm{m}_{\kappa}+\mathrm{J}_{\kappa}+\left(\mathrm{m}_{\kappa}+\mathrm{m}_{0}\right)\right)\ddot{\mathrm{z}}+\left(2\mathrm{iJ}_{0}\dot{\theta}_{0}\right)\dot{\mathrm{z}}+ \\ +\left(\mathrm{m}_{\kappa}+\mathrm{iJ}_{0}\ddot{\theta}_{0}\right)\mathrm{z}=\mathrm{m}_{0}\mathrm{r}_{0}\left(\dot{\theta}_{0}^{2}-\mathrm{i}\ddot{\theta}_{0}\right)\mathrm{e}^{\mathrm{i}\theta_{0}} \\ \left(\mathrm{J}_{0}+\mathrm{m}_{0}\mathrm{r}_{0}^{2}\right)\ddot{\theta}_{0}+\mathrm{m}_{0}\mathrm{r}_{0}\mathrm{Im}\left[\ddot{\mathrm{z}}^{\mathrm{T}}\mathrm{e}^{-\mathrm{i}\theta_{0}}\right]+ \\ +\mathrm{iJ}_{0}\mathrm{Im}\left[\mathrm{z}^{-T}\mathrm{z}\right]=\mathrm{M}_{\theta}, \end{cases} \qquad (4)$$

where M_θ – external rotational moment, applied to the wheel.

In the study of stationary modes we assume that the wheel rotates at a constant angular speed $\dot{\theta}_0 = \omega$, then we can write this expression in the new form of a vector variable $w = ze^{-i\omega t}$.

In neutral mode of wheel rotation, which is characterized by an initial stage of its rotary movement, we will assume that for some values it is constant $w = w_* = const$, then the equation (4) can be written as follows:

$$\left(\omega\left(i-\omega\right)-\omega^{2}\left(m_{\kappa}+\left(J_{\kappa}+2J_{0}\right)\right)\right)w_{*}=m_{0}\omega^{2}. \qquad (5)$$

Transforming the equation (5), as a result we obtain the dependence ratio of imbalance mass on the reduced wheel mass in the absence of balancing rolling elements:

$$m_{0}=w\left(\frac{i}{\omega}-1-J_{\kappa}-2J_{0}-m_{\kappa}\right). \qquad (6)$$

We now consider neutral modes of wheel rotation, when rolling elements are located on the wheel and when the axial line of its center of rotation and angles that describe the position of balancing of rolling elements retain a permanent position in the rotating coordinate system. To find the dependence of mass of rolling elements and their quantity on imbalance mass in the system (6), we introduce the following assumptions

$$\ddot{w}=\dot{w}=0,\ \ddot{\theta}_{j}=\dot{\theta}_{j}=0,\ w=w_{*}=const,\ \theta_{j}=\theta_{j}^{*}=const.$$

The result is:

$$\begin{cases} \left(\left(i-\omega\right)\omega-\left(J_{\kappa}+2J_{0}\right)\omega^{2}-m\omega^{2}\right)\mathrm{w}_{*}= \\ \qquad =\omega^{2}\left(\sum_{j=0}^{N}m_{j}r_{j}e^{i\theta_{j}^{*}}\right) \\ \mathrm{Im}\left[\left(\mathrm{w}_{*}^{\mathrm{T}}\mathrm{a}\right)e^{-i\theta_{j}^{*}}\right]=0,\mathrm{j}=1\ldots N. \end{cases} \qquad (7)$$

Assuming that $w_* = 0$, from the first equation (7) we find the dependence:

$$\sum_{j=0}^{N}m_{j}r_{j}\mathrm{e}^{i\theta_{j}^{*}}=0. \qquad (8)$$

This dependence means that the center of gravity of the system formed by balancing rolling elements and imbalance lies at the point O, characterizing the rotation center of the wheel. Then, assume that all rolling elements have the same mass m_j and are located at the same distance r_j from the wheel center of rotation. In this case, it is possible to determine the number of rolling elements, necessary to balance the imbalance of the disc following the condition: $m_0r_0 \le 2m_jr_j$.

Based on the above it can be assumed that the presented equations written for the rotating wheel can be used to study the phenomenon of imbalance for any bladed fan wheel designs used in the cooling systems of power plants of locomotives.

It is known that wheel imbalance in the respective correction planes are expressed by complex numbers:

$$\overline{m_{0}}=m_{0}(\cos\theta_{0}+i\sin\theta_{0});$$
$$\overline{m_{1}}=m_{1}(\cos\theta_{1}+i\sin\theta_{1}), \qquad (9)$$

where m_0, m_1 are unbalanced mass and mass of rolling elements in the plane OXY;

θ_0 is an angle that determines location of unbalanced mass in the plane OXY;

θ_1 is an angle that determines location of rolling elements in the plane OXY.

Introducing the rotation angle of imbalance in relation to rolling elements, the current imbalance of a wheel in assembly depending on the angle with known values $m_0, m_j^/$ can be determined by the formulas:

$$\begin{cases} \overline{m_0}(\theta_1) = m_0(\theta_1)[\cos\theta_0(\theta_1) + i\sin\theta_0(\theta_1)], \\ \overline{m_j'}(\theta_1) = m_j'(\theta_1)[\cos\theta_j(\theta_1) + i\sin\theta_j(\theta_1)], \end{cases} \quad (10)$$

where $m_0(\theta_1), m_j'(\theta_1)$ are values of imbalance mass and masses of rolling elements depending on the angle in the plane OXY;

$\theta_0(\theta_1), \theta_j(\theta_1)$ are angles characterizing locations of unbalance mass and location of rolling elements in relation to the plane OXY.

Further, knowing values $m_0(\theta_1), m_j'(\theta_1)$, we form a function following conditions that are necessary to optimize a relative location of rolling elements with respect to imbalance. For such a function two conditions are required:

$$f(\theta_1) = (m_0 + m_j') \to \max;$$

$$f(\theta_1) = \left| m_0 - m_j' \right| \to \min. \quad (11)$$

To find a maximum of the function f(θ) its changes at various angles θ_1 in the range from zero to 360° were studied (Pic. 4).

The graph shows that for the exclusion of a blade wheel unbalance of the fan there must be compliance with the conditions under which rolling elements are positioned in relation to each other at an angle θ_1 = 180°. When changing the wheel peripheral rotation speed the angle θ_1 will be adjusted automatically, which will provide reliable dynamic balancing of the latter.

Let's calculate a mass of rolling cargo (spherical rolling elements) arranged movably in the hollow ring 5 (see. Pic. 3). In practice, fan wheels of cooling systems of water and oil of diesel locomotives TEP70 are subjected to static balancing where permitted imbalance is about 230 g·cm. Excessive imbalance is eliminated with welding of loads. In this case, these loads are made in the form of spherical rolling elements disposed in the hollow ring, which is rigidly fastened at the end faces of the blades of the fan wheel with external diameter of 200 cm [8].

The mass of one spherical rolling element (taking the diameter equal to 30 mm):

$$G^1_{rol.el.} = V\gamma = \frac{1}{6}\pi \cdot d^3\gamma = \frac{1}{6}3{,}14 \cdot 3{,}0^3 \cdot 7{,}8 = 110{,}2 \ g \quad (12)$$

The total number of spherical rolling elements on one fan wheel:

$$n = \frac{G_{load}}{G^1_{rol.el.}} = \frac{1157{,}1}{110{,}2} = 10{,}5 \ pcs. \quad (13)$$

where G_{load} is dead weight of balancing load.

We take 11 balls of 30 mm diameter. As a result, for manufacturing of a hollow ring 5 (see Pic. 3) in accordance with GOST 10704-91 we choose steel tubes electrically welded with an outer diameter D_o = 35 mm with wall thickness s = 1,4 mm, material St3 according to GOST 380-94 [9]. So we get a design [6] that avoids disbalance of a fan wheel.

Conclusion. The results of the study, representing the innovative development of fan wheels are recommended to be used by design bureaus of locomotive plants and research institutes of the rolling stock, as well as during modernization of cooling systems of diesel engines at repair factories and depots.

REFERENCES

1. Zhilin, G. A., Malinov, M. S., Rodov, A. M., Sulimtsev, I. I., Shifrin, M. G. Passenger diesel locomotive TEP 70 [*Passazhirskij teplovoz TEP 70*]. Moscow, Transport publ., 2003, 423 p.
2. Operation and maintenance of rolling stock: educational guide for railway universities [*Ekspluatacija i tehnicheskoe obsluzhivanie podvizhnogo sostava: Ucheb. posobie dlja vuzov zh.-d. transporta*]. Ed. by V. A. Gapanovich, V. I. Kiselev, I. K. Lakin. Moscow, «IRIS GROUP» publ., 2012, 576 p.
3. Kuzmich, V. D., Rudnev, V. S., Prosvirov, Yu. E. Locomotives. General Course. Textbook [*Lokomotivy. Obshhij kurs. Uchebnik*]. Moscow, TMC for education on railway transport, 2011, 582 p.
4. Dankovtsev, V. T., Kiselev, V. I., Chetvergov, V. A. Maintenance and repair of locomotives: textbook for railway universities [*Tehnicheskoe obsluzhivanie i remont lokomotivov: Uchebnik dlja vuzov zh.-d. transporta*]. Ed. by V. A. Chetvergov, V. I. Kiselev. Moscow, TMC for education on railway transport, 2007, 558 p.
5. Mikhalchenko, G. S., Kashnikov, V. N., Kossov, B. S., Simonov, V. A. Theory and design of locomotives: textbook for railway universities [*Teorija i konstrukcija lokomotivov: Uchebnik dlja vuzov zh.-d. transporta*]. Ed. by G. S. Mikhalchenko. Moscow, Marshrut publ., 2006, 584 p.
6. FIIP decision to grant a patent of the Russian Federation for invention see the application № 2014110477 / 11 dated 12.02.2015 [*Reshenie FIPS o vydache patenta RF na izobretenie po zajavke № 2014110477/11 ot 12.02.2015 g.*].
7. Bashta, T. M., Rudnev, S. S., Nekrasov, B. B. Hydraulics, hydraulic machines and hydraulic actuator. Textbook for mechanical engineering universities [*Gidravlika, gidromashiny i gidroprivod. Uchebnik dlja mashinostroitel'nyh vuzov*]. Moscow, Mashinostroenie publ., 2004, 392 p.
8. Filonov, S. P., Gibalov, A. I., Nikitin, E. A. [*et al*]. Diesel locomotive 2TE116 [*Teplovoz 2TE116*]. Moscow, Transport publ., 1996, 334 p.
9. Ponomarev, S. D., Andreeva, L. E. Calculation of elastic elements of machines and devices [*Raschet uprugih elementov mashin i priborov*]. Moscow, Mashinostroenie publ., 2008, 349 p. 1980, 326 p.

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