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The system of vibration diagnostics of bearing units with notch n-channel filter based on iterative-integrating converters

The system of early vibration diagnostics of bearing units of gas pumping units with the improved metrological characteristics is offered. This is achieved by using following rejector filter (FRF) based on N-channel structures using iterative-integrative transducers, a charge measuring amplifier with differential inputs, and a more effective diagnostic criterion. Greater efficiency of the proposed solutions was tested by their computer simulations compared with the known ones.

Introduction

Today, the problem of increasing the reliability of the gas transportation system of Ukraine (GSU) is acutely raised, which is one of the main national achievements. Gas turbine engines (GTDs) are the most responsible functional units of the GSU. Constantly increasing requirements for increasing the reliability and durability of structural elements and components of the GTE, which necessitates the improvement of methods and means for assessing the current technical state of the engine during its operation.

More than 40-50% of the failure of the GTD is due precisely to the defects of the bearing units. Currently, systems are used to protect the engine from global damage and to stop it in the event of emergencies. With the help of such a system, it is impossible to estimate with a sufficient accuracy the bearing condition at the early stage of the development of the defect [1].

The urgency is to solve the problem of reliable identification of damages of bearing units at an early stage of development, which is not being dealt with today. The most commonly used method is to use Fourier Transform (DFT), which is known to reduce its effectiveness in the presence of significant noise and noise. The other direction is the use of high-order digital filters, but their quick and accurate setup under certain conditions is problematic (the signal to noise ratio is significantly less than 1).

These problems create complexes of contradictory requirements, to the equipment, which puts this task in the category of relevant for measuring technique in the vibration diagnostics of bearing units at an early stage.

Piezoelectric accelerometers are commonly used for vibration analysis of bearing nodes, however, one of the main problems of their application is the presence of powerful interferences and network drives [2]. In addition, existing methods are mainly based on the use of narrow-band follow-up sampling filters. Metrological characteristics of which do not always satisfy the conditions of measurement of useful signals on the background of powerful interference caused by closely spaced rotary harmonics [3, 4].

The disadvantage of known methods for the implementation of barrier tracking filters is the high accuracy of the constant time required to obtain the desired barrier characteristic. In fact, with a slight change in the post-time failure, the characteristics completely disappear. [5]. Another problem is to reduce the effectiveness of existing diagnostic methods under realistic measurement conditions (the change in the signal/noise ratio is due to the change in load of the GTE and the change in the rotational speed of the shaft) [6].

The purpose of the development is a system of vibration diagnostics of bearing units of the GTE at the early stage of defect formation with improved metrological characteristics.

In order to eliminate the above-mentioned shortcomings the developed structure of the system is presented in Fig. 1 [7].

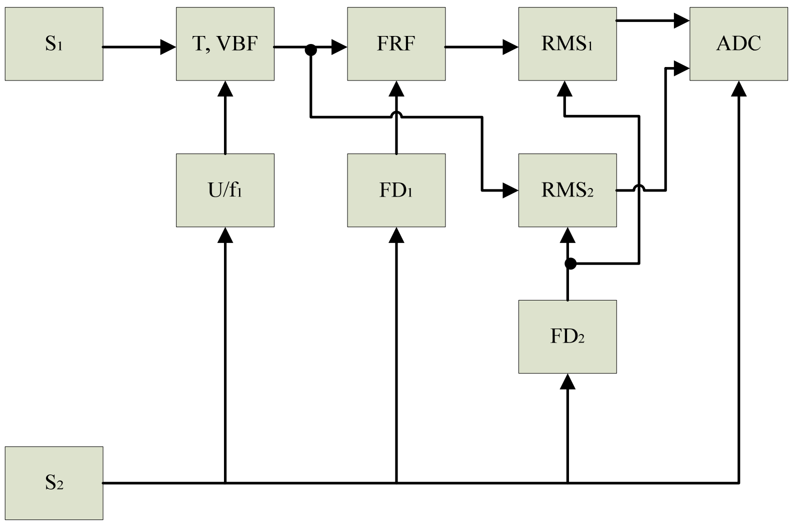

Fig. 1. Structural scheme of the system for vibration diagnostics of bearing units of the GTD

S_1 - piezoelectric sensor, S_2 - optical tachometer, T, VBF – trancducer, variable band filter, FRF - 4-channel following rejector filter, RMS_1, RMS_2 - detectors RMS (rout mean square), U/f_1 - frequency-voltage converter, FD_1, FD_2 - frequency dividers, ADC - analog-to-digital converter.

T, VBF performs the function of suppressing (decreasing) network drives and limiting the useful signal band at 1.6 octaves with increasing gain at the end of the range. To compensate for the unevenness of the frequency response of the 4-channel filter and to take into account the distribution of harmonics in the state of the bearings of rolling, as well as to compensate for possible high-frequency resonances.

Subsequently, the block of the N-channel tracking filter suppresses the harmonics of multiple rotational speeds of the shaft. The diagnostic criterion is formed in the logic-type ADC, which reduces the effect of the load shift of the GTD.

The device can operate in 2 modes of inspection and thorough.

In the survey mode, the whole frequency band of the bearing damage is analyzed. In this case, the bandwidth of the previous filter T, VBF is 1.6 octaves. In a careful mode, the bandwidth of the pre-filter T, VBF is narrowed to 1.3 octaves, and in this mode will actually pass a signal with a frequency corresponding to certain damage with the traces of the nearest rotor harmonics.

Model of the input (useful) signal of the diagnostic device

The output signal of the sensor S_1 can be represented as a Fourier series [8]:

$$U_g(t) = \sum_{n=1}^{6} A_n \sin(n\omega_0 t + \varphi_n) + \sum_{i=1}^{3} A_i \sin(\eta_i \omega_0 t + \varphi_i). \qquad (1)$$

Then the output signal of the follower selective filter takes the form of:

$$U_{T,VBF}(t) = \sum_{n=1}^{6} A_n \left|K_{T,VBF}(n\omega_0)\right| \cdot \sin(n\omega_0 t + \varphi_n + \varphi_{T,VBF}(n\omega_0)) + \qquad (2)$$
$$+ \sum_{i=1}^{3} A_i \left|K_{T,FRF}(\eta_i\omega_0)\right| \cdot \sin(\eta_i\omega_0 t + \varphi_i + \varphi_{T,FRF}(n\omega_0)),$$

An - amplitude of the *n* harmonic (rotor frequency) at the output of the sensor;
$n = 2 \ldots 6$ - harmonics of the rotor frequency;
$K_{T,VBF}$ - transmission coefficient variable band filter;
*A*i - amplitudes of the spectral components of bearing damage;
$i = 1, 2, 3$ - frequency number, which is responsible for certain damage;
φ_n, φ_i - initial phases of the corresponding harmonics at the output of the filter;
$\varphi_{T,VBF}$ - phase shift, which is introduced by the filter at this frequency;
ω_0 - frequency of rotation of the shaft (rotor);
η_i - coefficient of damage of rolling bearings;
$i = 1, 2, 3$

Table 1

Coefficients of damage the rolling bearings

Coefficient of damage	Name	Formula for calculation
η_1	Damage coefficient of the inner bearing ring	$\eta_1 = \frac{N}{2}\left(1 + \frac{B_d}{P_d}\cos\varphi\right)$
η_2	Damage coefficient of outer bearing ring	$\eta_2 = \frac{N}{2}\left(1 - \frac{B_d}{P_d}\cos\varphi\right)$

η_3	The coefficient of damage of rolling bearings of the bearing	$\eta_3 = \frac{P_d}{2 \cdot B_d}\left(1-(\frac{B_d}{P_d}\cos\varphi)^2\right)$

N - number of bodies of rolling;
B_d - diameter of rolling bodies;
P_d - mean diameter of bearing roller;
φ - angle of the contact.

At the input of the logometric ADC, we will have signals proportional to the sum of the squares of the active values of the spectral components of the input signals:

$$U_{RMS1} = K_{RMS1} T_a \left\{ \sqrt{\sum_{i=1}^{3} [A_i \left|K_{T,VBF}(\eta_i\omega_0)\right| \cdot \left|K_{FRF}(\eta_i\omega_0)\right|]^2} \right\}, \tag{3}$$

K_{RMS1} - transfer factor of the detector of square root mean square values RMS_1;
T_a - time of analysis;
$K_{T,VBF}$ - transmitter ratio of the N-channel filter at frequencies corresponding to certain damage;
K_{FRF} - the transfer coefficient of the following rejector filter.
Present U_{RMS2} as:

$$U_{RMS2} = K_{RMS2} T_a \left\{ \sqrt{\sum_{i=1}^{3} [A_i \left|K_{T,VBF}(\eta_i\omega_o)\right| \left|K_{FRF}(\eta_i\omega_o)\right|]\mathrm{I} + \sum_{n=1}^{6} [A_n \left|K_{T,VBF}(n\omega_o)\right|]^2} \right\}, \tag{4}$$

K_{RMS2} - transmittance ratio of the detector $RMS2$.

As a generalized vibration diagnostic criterion, we will choose the ratio of stresses at the outputs of the RMS detectors:

$$\theta = \frac{U_{RMS1}}{U_{RMS2}}. \tag{5}$$

Given that $RMS_1 \approx RMS_2$, and $\sum_{n=1}^{6} \gg \sum_{i=1}^{3} -$ expression (5) will look like:

$$\theta = \sqrt{1 + \frac{\sum_{i=1}^{3} [A_i \left|K_{T,VBF}(\eta_i\omega_o)\right| \left|K_{FRF}(\eta_i\omega_o)\right|]\mathrm{I}}{\sum_{n=1}^{6} [A_n \left|K_{T,VBF}(n\omega_o)\right|]\mathrm{I}}}, \tag{6}$$

or

$$\theta - 1 \approx 0,5\frac{\sum_{i=1}^{3}[A_i\left|K_{T,VBF}\left(\eta_i\omega_o\right)\right|\cdot\left|K_{FRF}\left(\eta_i\omega_o\right)\right|]\mathrm{I}}{\sum_{n=1}^{6}[A_n\left|K_{T,VBF}\left(n\omega_o\right)\right|]\mathrm{I}}. \qquad (7)$$

The choice of time analysis (T_a) is important. The control of the T, FRF is carried out with the aid of a speed sensor of the GTE shaft, as appropriate, to use an optical tachometer and a frequency-voltage converter for controlling a universal voltage-controlled filter. Frequency dividers with *n* and *m* fission coefficients are needed to obtain the synchronization signals of the FRF and to form the analysis time T_a, respectively. If we denote the coefficient of conversion of the frequency of rotation of the GTE shaft by the sensor S_2 - K_1, then the dividing factor *n* in the divider FD_1 can be represented as:

$$n = \frac{K_1}{4}, \quad m = \frac{K_1 f_{0\min}}{f_{\min b}}, \qquad (8)$$

f_{minb} - the minimum beat frequency, will be determined by the distribution of the spectral components of the useful signal;
$f_{0\min}$ - minimum speed of rotor rotation.

Optimization of the follower rejector filter

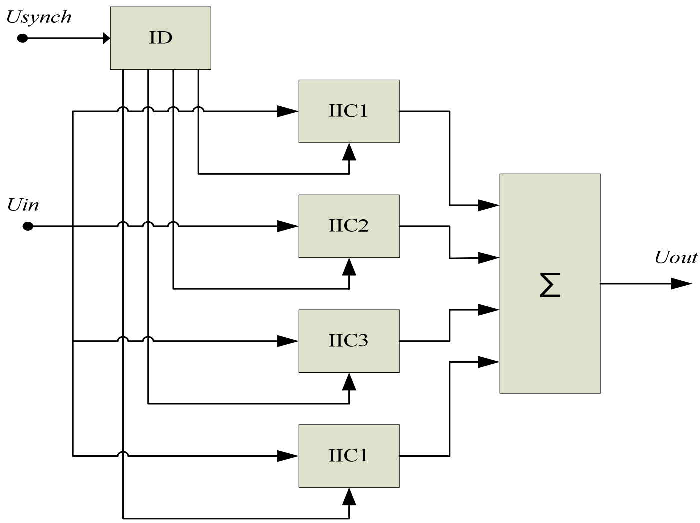

Fig. 2 Structural scheme of the follower reject filter
IIC1-IIC4 - iterative-integrating converters;
PD - pulse distributor for 4;
Σ - adder.

In fig. 3 shows the amplitude-frequency characteristics (AFC) filters with different coefficients of window duration (0.75, 1, 1.25), while it can be seen that the filter with sequential windows (k = 1) has the slightest non-uniformity of the amplitude-frequency characteristic.

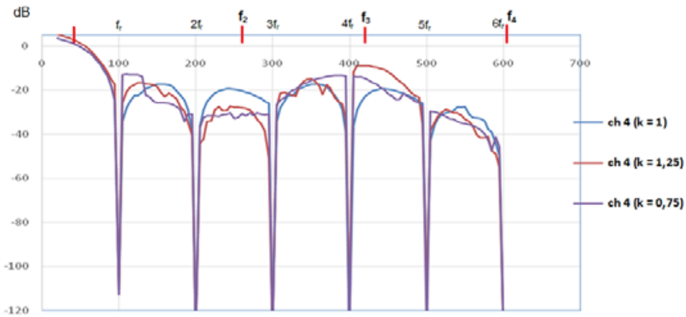

Fig. 3. Amplitude-frequency characteristics of 4-channel filters

Development and simulation of amplifiers for work with piezoelectric sensors

One more destabilizing factor when working with piezoelectric sensors is network interference of the general and normal type. In [9], it is proposed to use the classical scheme of a measuring amplifier based on the three operational amplifiers presented in Fig. 4. In this case, as a sensor, a normal piezoelectric sensor is used. When using a differential sensor in this circuit, the results may be much worse due to the asymmetry of the sensor itself. The disadvantages of such a solution include the significant penetration of the network voltage through the interconnecting capacitance of the power transformer, due to the asymmetry of the input terminals.

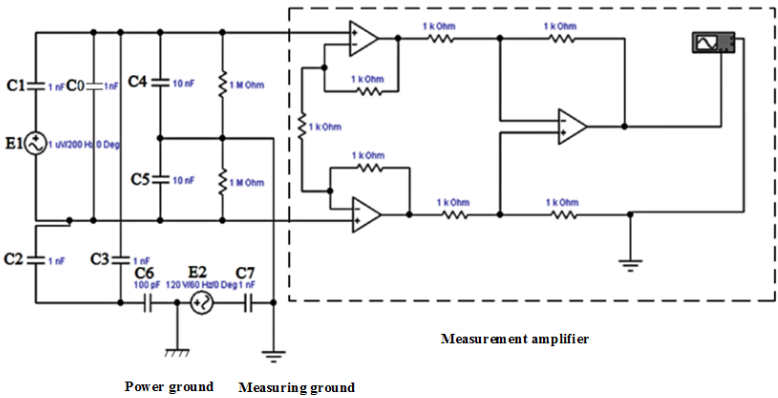

Fig. 4. Functional scheme of an electrometric measuring amplifier for working with piezoelectric sensors

In the scheme, the sensor is represented by an equivalent voltage generator E1 and a capacity C1. C0 is the capacity between the conductors of the connecting cable. C2, C3 are parasitic capacitances between the conductors of the connecting cable (twisted pair on the screen) and the screen. C6 parasitic capacitance between the cable bundle and the ground of the power grid. E2 is an equivalent network voltage generator (110 V, 50 Hz), C7 is the capacitance between the windings of the power transformer. Elements E2, C7 are formed due to the fact that at the network frequency (50 Hz) the distributed capacitance between the windings of the power transformer can be replaced by a concentrated capacity (C7) between the middle of the windings of the power transformer. In the balanced version at C2 = C3, C4 = C5 and the input voltage E1 = 1 V, the signal-to-noise ratio at the output of the amplifier will be 115 dB.

With the asymmetry of capacities C2, C3 at 10%, the signal to noise ratio decreases to 4 dB, making the measurement practically impossible.

In fig. 5 presents the proposed functional scheme of the amplifier for work with piezoelectric sensors free of the above mentioned disadvantages.

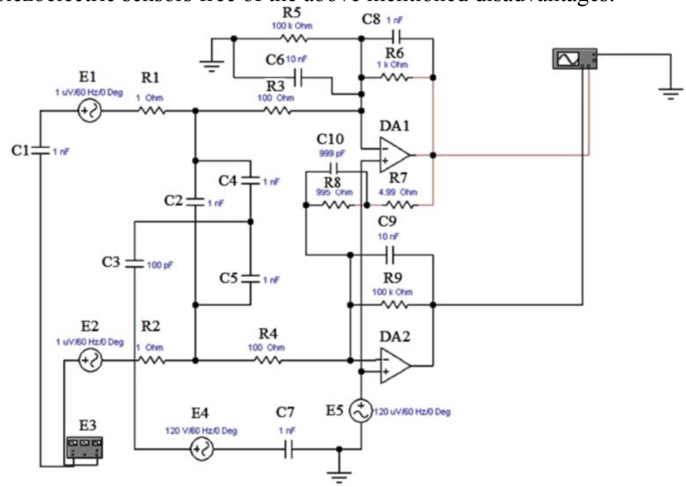

Fig. 5. Functional scheme of a charge measuring amplifier with differential-current inputs for work with piezoelectric sensors

The basis of the circuit is a measuring charge amplifier with differential-current inputs made on the operational amplifiers DA1, DA2. The piezoelectric sensor is connected to the inputs of this amplifier. In this case, the cascade on amplifiers DA1 performs the function of the current inverter feedback elements R9, C9 form the low-frequency pole of the fmplitude-frequency characteristics of the amplifier. Output voltage will be equal to:

$$U_{out} = 2e_D \frac{c_D}{c_9}, \tag{11}$$

e_D - the equivalent output voltage of the sensor;

c_D - electrical capacity of the sensor;

c_9 - electrical capacity of the C9.

To determine the impedance of this amplifier, a model was created in the Electronics Workbench software environment. Connection of the sensor to the measuring amplifier is carried out using a twisted pair cable on the screen.

C1 - equivalent capacitance of the sensor;

E3 - equivalent output voltage of the sensor;

That is, the sensor is modeled according to the scheme of the equivalent voltage source: C1, E3.

R1, R2, R3, R4 - serial cables of cable wires;

C2 - the capacity between the cables of the cable; C4, C5 - capacitance between live cable and screen;

E1, E2 are equivalent generators of voltage disturbances of the normal form, which are given in each cable core by the equivalent scheme given in [10] by external electromagnetic fields;

E4 is the equivalent voltage of the general form, which arises at the expense of the capacity between the windings of power transformers;

C7 - the capacity between the windings of the power transformer;

C3 - parasitic capacitance between the blister (screen) of the input cable and the network ground;

E5 - the equivalent source of the general kind which arises at the expense of general resistances of grounding links;

C10, R8, R7 - corrective circuit is not ideal of frequency characteristic DA1.

The current inverter is made on the operating amplifier DA1 with R6≈R7 + R8, and C8 is the correction capacitance for excitation blocking. Elements R9, C9 perform the function of decoupling inputs of the operational amplifier DA2 by direct current and form a low-frequency pole of the frequency response. The correction link DA1, R5, C6 is chosen so that R5 = R9, and C6 = C9 to neutralize the influence of the source E5.

Similarly, in the previous case, the signal / noise ratio at the output of the amplifier penetrating network interference sources E4 on the output of the amplifier was performed at 10% of the imbalance of capacities of the input cable C4, C5 and it was determined that it is - 30 dB. It is 26 dB better than in the previous electrometric measuring amplifier.

Conclusions

The structural scheme of the measuring channel for the early diagnostics of bearing units was developed. The features of this are the use of a follow-up N-channel rejector filter based on iterative-integrating converters.

The 4-channel following rejector filters were investigated and AFC with different window duration coefficients (k = 0.75, k = 1, k = 1.25) were investigated, it was found that a filter with sequential windows at (k = 1) has the smallest unevenness of the amplitude-frequency characteristic.

A functional scheme of the measuring charge amplifier with differential inputs was developed. With the simulation in the software environment, Electronics Workbench shows the benefits of the proposed amplifier in comparison with the known technical solutions.

A diagnostic criterion is proposed, which allows taking into account the change in the load of the GTD.

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