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FUEL DISTRIBUTOR CONTROL OF AN INTERNAL COMBUSTION ENGINE USING HILBERT-HUANG TRANSFORMATION

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ABSTRACT

Article purpose: to consider the possibility of Hilbert-Huang transformation (HHT) use for vibration-acoustic control of a fuel dispenser operation in an internal combustion engine HHT was proposed by Norden Huang in 1995 to study the surface waves of typhoons. In recent years, the method has been actively used in geophysics, medicine, radio engineering, etc. Hilbert-Huang transformation makes it possible to extract information from signals about the rapid temporal changes of their spectral composition. HHT is the method of empirical mode decomposition of signals and Hilbert spectral analysis.

The article presents the results of vibration-acoustic signal processing of an internal combustion engine using HHT. The series of experiments was carried out in a test laboratory on a motorized bench (eight-cylinder two-stroke engine). The measurements of vibration-acoustic signals were carried out for the periods when the engine operates in normal mode and when one of the cylinders is not working (the supply to the fuel dispenser is switched off). It was determined that the 9th empirical mode (Intrinsic mode functions) contains the basic harmonic components of a signal. When the fuel dispenser of one of the cylinders is disconnected, the asymmetry of the instantaneous frequencies distribution of the 9th IMF appears relative to their average value. During the analysis of their central third-order moment, it is possible to establish the state of the controlled object properly.

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Keywords: Hilbert-Huang transformation, empirical mode decomposition by ensemble, instantaneous frequency, third-order central moment, nondestructive testing, internal combustion engine, vibration-acoustic signal.

1 INTRODUCTION

The prerequisite for the troubleshooting in mechanical equipment according to vibration-acoustic parameters is that the vibration signal of a monitored product contains a large amount of information about its state. An effective use of vibration-acoustic control requires a proper extraction of this information from vibration signals.

Traditionally, Fourier transformation is used to process vibration signals. In some cases, it is not enough to assess the state of a control object. This is related to the fact that Fourier transformation does not reveal the behavior of the spectral components in time.

In many modern diagnostic systems, the problem of frequency-time signal conversion is solved using wavelet analysis [1-3]. However, the reliability of such an analysis largely depends on the choice of the basic function by which a signal is converted. In this regard, the problem of an adaptive basis development appears for the frequency-time transformation functionally dependent on the content of the vibration-acoustic signals. This problem can be solved by the application of Hilbert-Huang transformation, which does not require an a priori functional transformation basis [4-13]. Here, the basic functions are obtained adaptively directly from the signals by the empirical mode (Intrinsic Mode Functions, IMF) removal procedures. The method was proposed by Norden Huang in the USA (NASA) in 1995 for the study of typhoon surface waves, with the generalization to the analysis of arbitrary time series by the team of coauthors in 1998. In recent years, the method has been actively used in geophysics, medicine, radio engineering, etc.

Article purpose: to consider the possibility of Hilbert-Huang transformation application for vibration acoustic control of a fuel dispenser operation in an internal combustion engine.

2. METHODS

The series of experiments was carried out in a test laboratory on a motorized bench (eight-cylinder two-stroke engine).

The measurements of vibration-acoustic signals were carried out for the periods when the engine operates in normal mode and when one of the cylinders is not working (the supply of power to a fuel dispenser is switched off). The structural scheme of the measuring system [14,15] is presented on Figure 1.

Fig.1. Block diagram of the measuring system, where LV is the laser vibrometer LV-2, ADC - NI USB-6251 analog-to-digital converter with 16-bit resolution, PC - personal computer with LabVIEW software

The laser vibrometer was installed at the distance of 2 meters from the motor stand and its beam was aimed at the cylinder head, the deenergizing of which was assumed in the course of the experiments.

The work of the motor stand was carried out with the crankshaft speed of 2200 rpm. The registration of vibration-acoustic signals was carried out with the sampling frequency of 40000 Hz.

Hilbert-Huang method was applied in order to process the vibration-acoustic signals. This method includes the modal decomposition procedure according to the ensemble, which is the following [4,16-18].

1. White noise ξn with a given signal-to-noise ratio is added to the signal y (t):

$$y_{\xi}(t) = y(t) + \xi_n \quad (1)$$

2. The position of local extrema is determined in the signal yξ (t) (all peaks and depressions are determined).

3. The upper u_a(t) and the lower u_b(t) enveloping the process, respectively, passing through the maxima and the minima of a normalized signal, are calculated by the cubic spline. The function of average values m_1(t) is determined between the envelopes:

$$m_1(t) = \frac{u_a(t) + u_b(t)}{2} \quad (2)$$

The difference between the signal y_{ξ}(t) and the function m_1(t) gives the first screening component - the function h_1(t), which is the first approximation to the first IMF function:

$$h_1(t) = y(t) - m_1(t).$$

(3)

4. The operations 2 and 3 are repeated, taking the function $h_1(t)$ instead of y(t), and the second approximation to the first function IMF -the function $h_2(t)$ is obtained.

$$h_2(t) = h_1(t) - m_2(t).$$

(4)

The stopping of the screening operations is carried out according to the specified limitation of iteration number (no more than 10).

5. The last value of $h_i(t)$ iterations is taken as the highest-frequency function $c_1(t) = h_i(t)$ of IMF family, which is directly included in the signal $y_\xi(t)$. This allows to subtract $c_1(t)$ from the signal composition and leave the lower-frequency components $r_1(t)$ in it:

$$r_1(t) = y_\xi(t) - c_1(t). \quad (5)$$

6. The resulting remainder $r_1(t)$ becomes a new time series for the decomposition, the operations 2-5 are repeated. The decomposition is completed when the remainder $r_n(t)$ is a monotonic function.

7. Steps 1-6 are repeated N_E times (where N_E is an ensemble number). Here, each time a new-generated noise ξn is added to the signal y(t), the result of the decomposition is stored at each step.

8. The selected modes are averaged over the ensemble:

$$s_i(t) = \tilde{c}_i(t),$$

(6)

where $\tilde{c}_i(t)$ is the *i*-th IMF function averaged over the ensemble.

9. The function v(t) is determined, conjugated to IMF by Hilbert:

$$v(t) = F^{-1}\{-j\,\mathrm{sgn}(f)X(f)\},$$

(7)

where F^1 is the inverse Fourier transformation, *X*(*f*) is the transformation result Fourier functions *s*(*t*) IMF, $\mathrm{sgn} = \begin{cases} 1 & f > 0 \\ 0 & f = 0 \\ -1 & f < 0 \end{cases}$, *f* – signal harmonic.

10. The instantaneous frequency w(t) and the amplitude a(t) values are calculated for each IMF.

Instantaneous amplitude:

$$a(t) = \sqrt{s^2(t) + v^2(t)},$$

(8)

where s(t) is the ensemble-averaged IMF function, v(t) is the function conjugated to the Hilbert IMF.

Instantaneous frequency:

$$w(t) = \dot{\varphi}(t) = \frac{s(t)\dot{v}(t) - \dot{s}(t)v(t)}{a^2(t)},$$

(9)

where $\varphi(t) = arctg\left(\frac{v(t)}{s(t)}\right)$ is an instantaneous phase.

The signals were processed and analyzed using the programs written in the LabVIEW programming environment.

3. RESULTS

In the process of signal processing in accordance with the modal decomposition procedure according to the ensemble, white noise ξ_n is added to the signal with the signal-to-noise ratio of 18.7 dB, the ensemble number N_E = 100.

The results of vibration-acoustic signal processing can be represented on the intensity charts (obtain the Hilbert spectra), where the amplitude value is indicated on the frequency-time plane by a corresponding color. Hilbert spectra for the engines with a properly operating fuel dispenser and disconnected are presented on Figure 2 and on Figure 3.

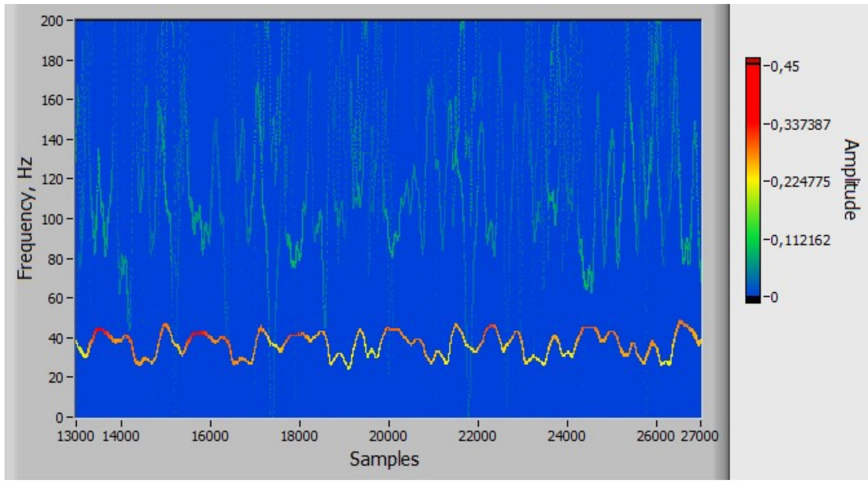

Fig.2. Hilbert's spectrum of a properly working engine

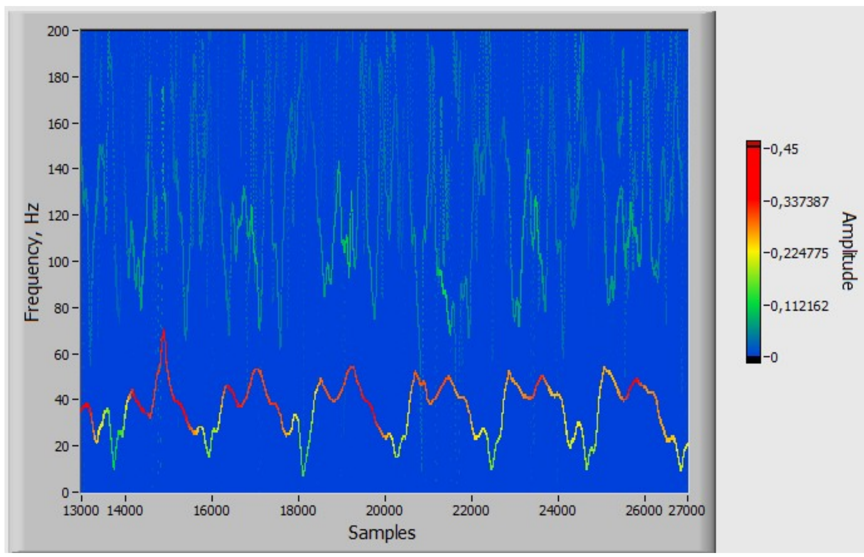

Fig.3. Hilbert's engine spectrum with a turned off fuel dispenser of one of the cylinders

Figure 2 and Figure 3 show that when a fuel dispenser is switched off, the appearance of new frequency components is clearly visible on the Hilbert spectra, while the differences in Fourier spectra (Figure 4 and Figure 5) are not significant.

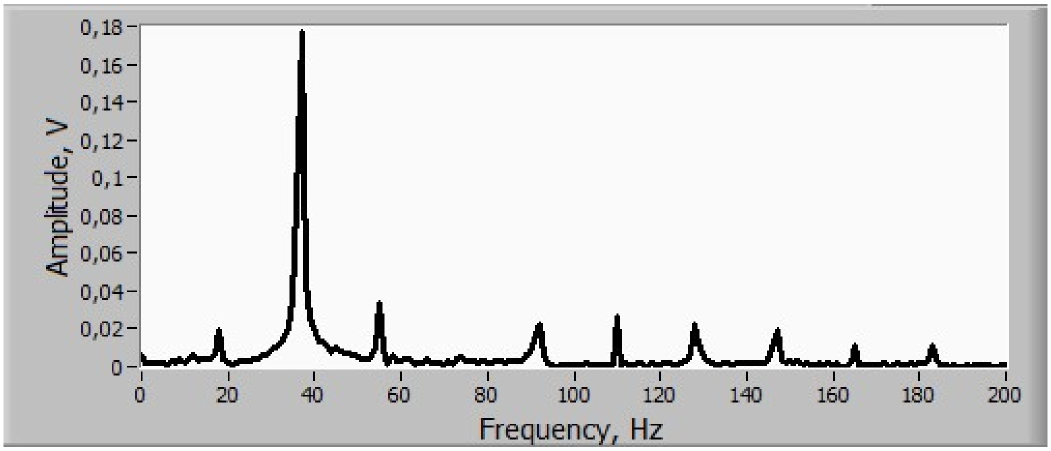

Fig.4. Fourier spectrum for a properly working engine

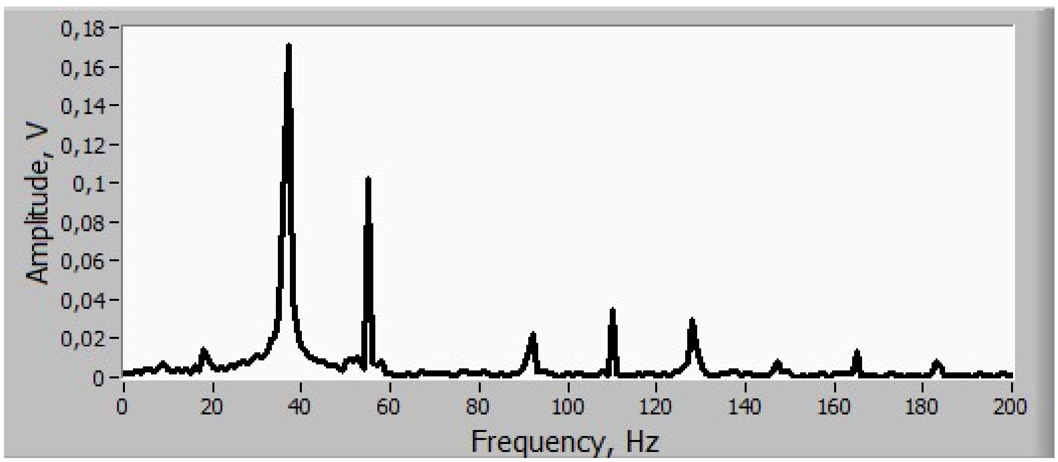

Fig.5. Fourier spectrum of the engine with a turned off fuel dispenser on one of the cylinders

4. DISCUSSION

Hilbert spectra are simple in interpretation and allow us to obtain a qualitative picture of harmonic component distribution in time. However, the graphs of instantaneous frequency dependencies on time are not inferior in clarity to Hilbert spectra and are more convenient from the point of view of analysis by numerical methods. It is established that the 9th IMF contains the basic harmonic components of a signal.

The graphs of instantaneous frequency change of the 9th IMF are shown on Figure 6 and Figure 7.

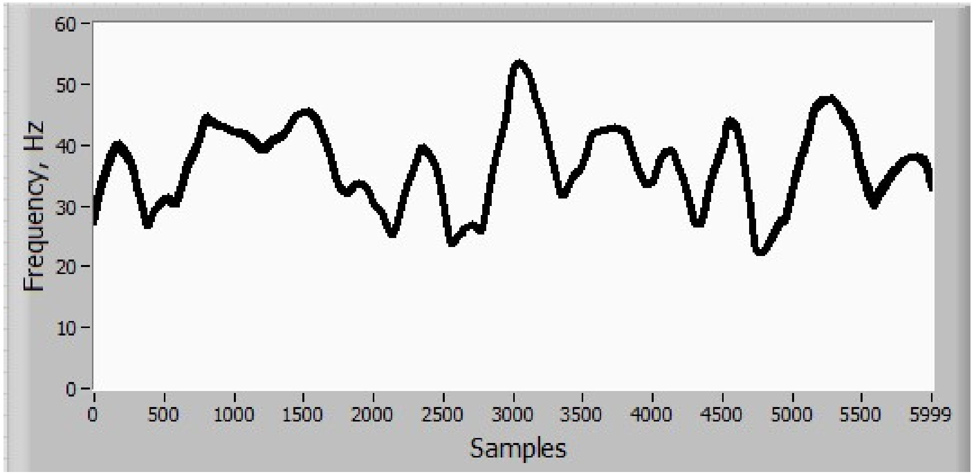

Fig.6. Instantaneous frequencies of the 9th IMF of a properly working engine

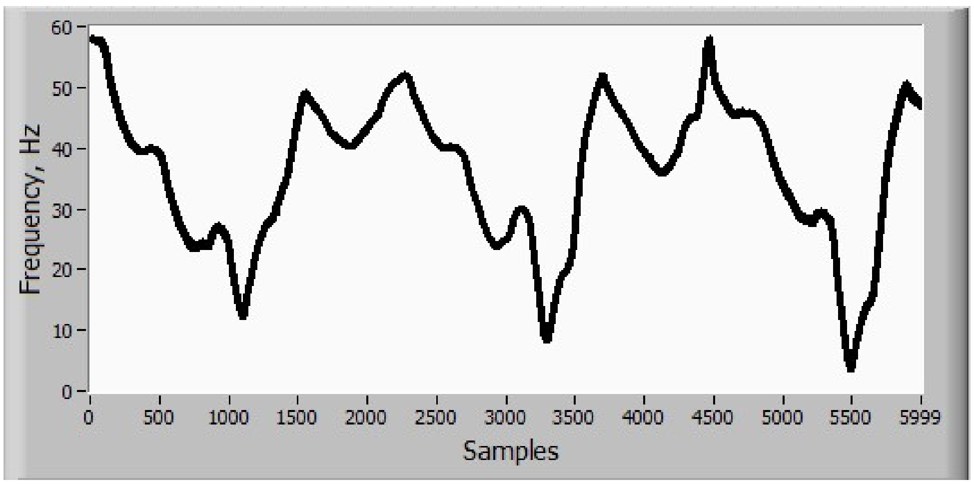

Fig.7. Instantaneous frequencies of the 9th IMF of the engine with a turned off fuel dispenser from one of the cylinders

Figure 6 and Figure 7 show that the harmonic components of the 9th IMF are concentrated relative to the 36.7 Hz mark. This frequency corresponds to the speed of the crankshaft (2200 rpm) set during the experiments. When a fuel dispenser of one of the cylinders is turned off, the asymmetry of instantaneous frequency distribution appears relative to their mean values. In order to assess the degree of their symmetry, one can use the central third-order moment:

$$\sigma_w^3 = \frac{1}{n}\sum_{i=0}^{n-1}(w_i - \overline{w})^3, \tag{10}$$

where n is the number of frequency sequence elements w, $\overline{w}$ is the mean value.

In order to classify an object of control into "suitable" or "failed" the approach typical for the procedure of anomaly rejection is proposed [14,19,20]. For this purpose, the set of computed values of the third-order central moment is interpreted as the set of measured values (p_1, p_2, ..., p_m) of some abstract parameter and the following algorithm is applied:

1) Position estimation $\overline{p}$ is calculated;

2) the variance estimate S is calculated as an average absolute deviation;

3) the confidence interval α is developed for a given level of significance:

$$\overline{p} \pm St(1-\frac{\alpha}{2}, m-2), \tag{11}$$

where *t(α,m)* is the α-quantile of Student's distribution with m degrees of freedom.

Figure 8 shows the results of central moment comparison (for the 9th IMF) with the confidence interval limits formed in accordance with the significance level of 0.05. The sample length for the determination σ_w^3 is taken as 6 thousand calculations.

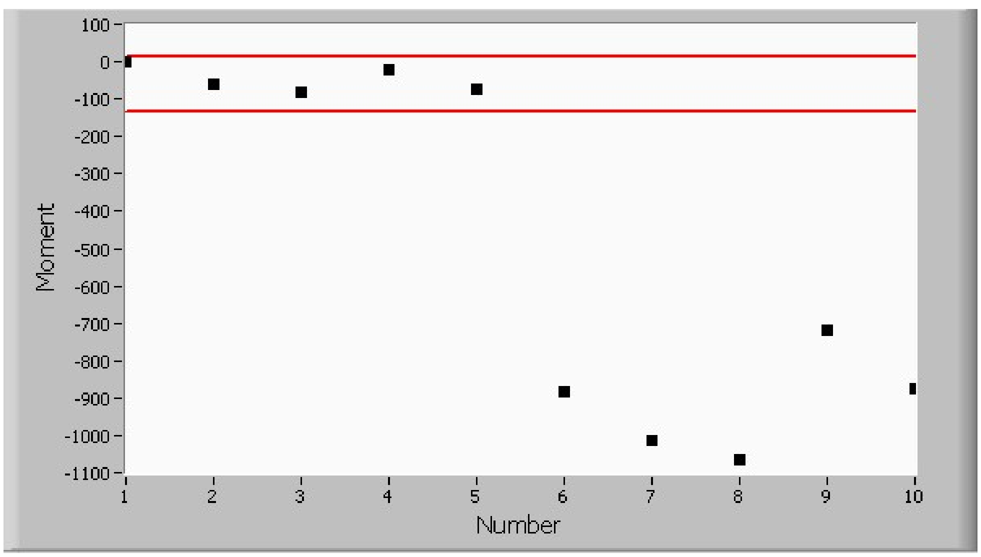

Fig.8. Comparison of the values concerning the third-order central moments with the boundaries of the confidence interval (red lines)

Первые пять значений на Рисунке 8 соответствуют сигналам исправно работающего двигателя, а значения с номерами 6-10 – сигналам двигателя с отключенным топливным дозатором одного из цилиндров.

5 CONCLUSIONS

The central moments σ_w^3 located close to zero characterize the serviceable state of the engine and demonstrate the symmetry of instantaneous frequency distribution with respect to their mean value. When the fuel dispenser of one of the cylinders is turned off, an significant asymmetry appears, at which the values σ_w^3 go beyond the limits of the confident interval.

6 SUMMARY

Hilbert-Huang transformation makes it possible to extract information from the signals about the rapid temporal changes in their spectral composition. In this case, there is no need to choose the basis decomposition function, on which the resolving power of the frequency-time transformation depends largely. The graphs of IMF instantaneous frequency change are not inferior in clarity to Hilbert spectra and are more convenient from the point of view of analysis by numerical methods. It is established that the 9th IMF carries the basic harmonic components of a signal. When the fuel dispenser of one of the cylinders is disconnected, the asymmetry of the instantaneous frequencies distribution of the 9th IMF appears relative to their average value. Analyzing their central third-order moment, it is possible to establish a controlled object state reliably.

7 ACKNOWLEDGEMENTS

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