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Determination of Dynamic Range of Stand-alone Shock Recorders

Anzhelika Stakhova [1], Yurii Kyrychuk[2], Nataliia Nazarenko[3]

[1]*Department of Computerized Electrical Systems and Technologies, Aerospace Faculty, National Aviation University, Liubomyra Huzara ave., No.1, 03058, Kyiv, Ukraine, sap@nau.edu.ua*
[2]*Department of Automation and Non-Destructive Testing Systems, Faculty of Instrumentation Engineering, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Peremohy ave., No.37, 03056, Kyiv, Ukraine*
[3]*Department of Automation and Non-Destructive Testing Systems, Faculty of Instrumentation Engineering, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Peremohy ave., No.37, 03056, Kyiv, Ukraine*

Abstract: In aircraft construction, when creating samples of new equipment, shock tests are often performed, both on individual components and the entire product. It requires introducing non-destructive testing devices into production, it is one of the most important factors in accelerating scientific and technological progress, raising the quality and competitiveness of manufactured products. Applying modern means of non-destructive testing, there is the problem of their protection from external vibrations, which affect the sensitivity, accuracy and reliability of high-precision measurements. In such cases, the conversion of measuring information during powerful vibration and shock tests, as a rule, is carried out by piezoelectric acceleration sensors. Although to provide impact testing, there is a need to develop and use stand-alone recorders. The main requirements for these recorders are to ensure the autonomy and operability of the recorder onboard the test product and to ensure the synchronization of the registration of the shock load.

Keywords: non-destructive testing, shock tests, measurements, sensitivity, accuracy, external vibrations.

1. Introduction

Improvement of technical and economic indicators of machines and equipment is required and it is carried out by increasing their power and operating speeds while reducing weight, which increases the level of vibration [1]. Control over the compliance of vibration parameters with the requirements of current sanitary norms is carried out at the stage of design, manufacture and operation of equipment [2], [3]. However, modern precision instrumentation requires testing of instruments and systems in conditions of maximum realism that is close to real operating conditions [1], [4].

When testing objects, there is a need to develop and use small, portable, autonomous recording devices that work directly on tested objects under vibration load [5].

Operation of the recorder directly on the tested object in the conditions of vibration loading imposes the following special requirements on the recorder: small dimensions and weight; autonomy; vibration and shock resistance; insensitivity to electromagnetic radiation; and wide temperature range [6]-[7]. In such conditions, the value of the reliability of hardware and algorithmic support of the measurement process increases many times over.

It is necessary to ensure the autonomy of the recording equipment onboard the sample of equipment, ensure synchronization of the course of registration of measuring information, and storage and transmission of information in a computer with subsequent rapid analysis of registered information.

Autonomy is the main property of the recorder, which indicates its ability to provide its functionality without additional support. It means the energy, design and functional independence of the recorders when taking measurements under heavy load [6]-[7].

Operation of the recorder in the independent mode directly on the tested object in the conditions of loading imposes special requirements on the recorder. They are that the recorder must be autonomous, small, and highly reliable and have a minimum set of functional nodes in the channel - an amplifier, ADC, microprocessor and storage device, as well as not being serviced [6]-[7]. All other necessary functions must be provided by the control panel and connected to the recorder during maintenance and testing of the stand-alone recorder.

Functional autonomy is the ability of the recorder to perform basic functions without the control command "outside". It is assumed that preparation for work is carried out a priori. To ensure functional autonomy, the recorder must have several properties:

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- internal management of all elements;
- automatic transfer from registration mode to standby mode or information issuance mode;
- the ability to program a priori a minimum set of basic parameters of the recorder.

To ensure compliance with the requirements for the recorder, it is necessary to use the following principles and methods of building recorders:

- structural methods to ensure measurement accuracy and operational reliability;
- use of vibration and thermostable electronic components;
- use of structural damping of boards and separate electronic components, and depreciation of electronic units and especially the power supply unit of the recorder.

The issues of structural methods to ensure measurement accuracy and operational reliability will be considered in this paper.

The main criteria for choosing the structure of the recorder are [6]-[7].

- providing the maximum frequency and dynamic ranges without switching the gain and frequency characteristics of the channel;
- ensuring the maximum speed (oversampling) of the ADC, the maximum bit size of the ADC, and the maximum possible amount of memory;
- minimization of the number of structural elements of the recorder;
- ensuring maximum autonomy of the recorder's channels;
- functional flexibility of the recorder structure development;
- minimum energy consumption during registration and storage of information;
- ensuring high reliability of the recorder.

Impact tests are often one-off and destructive to products, which significantly increases the requirements for calibration and parameterization of output channels [6]-[7]. Piezoelectric accelerometers used in the study have pronounced resonant properties. The operating range of the sensor selects no more than half the resonant frequency of the sensor. Prior information about the various shock effects contains significant differences, as it is obtained based on rather rough estimates. In this case, when conducting the tested spectrum of exposure, it is possible to achieve the resonant frequency of the sensor, which can lead to overload from the measuring channel.

In addition, a fairly low-frequency shock can be accompanied by high-frequency mechanical perturbations, which also lead to overload from the measuring channel. Switching of acceleration coefficients and measurement of frequency characteristics in autonomous registration is very difficult (and in the process of testing and operation is impossible), as it reduces the reliability of recorders, devices, and energy costs.

This is a really important task: to provide a dynamic range without the use of switching actions on the measurement signal.

2. SUBJECT & METHODS

When developing stand-alone recorders, the problem is in providing a dynamic range of the measuring channel of the recorder with a given accuracy of registration of the shock signal and the vibration signal in a non-switching way, i.e. without switching the gain and changing the frequency characteristics of the channel. It should be noted that the problem of non-switching provision of the dynamic range of the measuring channel is especially relevant when measuring transient shock processes where incorrect initial determinations of accelerations and, as a consequence, overload are possible [8].

Adjusting the gain and frequency characteristics of the channel in a stand-alone recorder is very difficult (and in the process of testing impossible) because it is associated with a decrease in the reliability of the recorder, hardware, and energy costs.

The purpose of each test is to establish certain properties of the object under study in order to control its qualitative characteristics. To ensure the dynamic range of the measuring channel range, the recorder proposes to use the following devices and algorithmic tools - multi-bit ADC with high resolution; high-efficiency filtering of the input signal, which amplifies the registration (most often looking for a signal), and forgets the sound recording signal in the computer by the known transmitted function of the filter in the amplifying recorder.

The conversion of measurement information during the tests, as a rule, is carried out by piezoelectric acceleration sensors of different sensitivity [16]. These sensors have pronounced resonant properties. The choice of piezoaccelerometers is that the frequency of the setting resonance exceeds the upper frequency of the spectrum of the acceleration signal, usually three times, and the expected total value of the acceleration is less than the linearity range of the accelerometer with a margin of about 30 % [9].

Particular emphasis should be placed on the problem of providing dynamic range without gain switching, as the solution to this problem eliminates overload (invalid measurements) and allows coordinating the dynamic range of sensors and recording equipment. Accurate measurement is obtained from the first measurement even when using mixed sensors.

To select the ADC difference, it is necessary to develop a method for estimating the dynamic range of the recorder range according to the known value of the ADC parameters (bit rate, number of effective bits, signal-to-noise ratio).

According to [10], the true dynamic range of the ADC determines the relationship between the magnitudes of the converted load on the RMS (root mean square) of the total noise component in digitization systems.

$$D_{AD} = 20\log\left[\left(2^M - 1\right)\sqrt{\frac{12}{1+b^2}}\right];\quad b = \frac{\sqrt{12}\sigma_\Sigma}{\Delta}, \qquad (1)$$

where σ_Σ is RMS and is the sum of internal and external noises in the digitization system.

From (1) it is seen that the dynamic range of the ADC is defined in [13] by an expression that does not include the error of signal measurement, and for shock tests under uncertainty of the input signal amplitude, such determination of the dynamic range of the recorder is incorrect because we need to digitize and register the signal with a given accuracy.

The maximum relative error of digitization of the amplitude of the shock pulse is determined by the ratio of the noise level of the ADC to the amplitude of the pulse (for an ideal ADC, the noise level is equal to the quantization step)

$$\delta = \gamma\Delta / A = \gamma u_m 2^{-M+1} / A, \tag{2}$$

where Δ is the step of quantizing the input signal by voltage, u_m is maximum ADC input voltage, A is shock pulse amplitude (input signal to ADC), M is the number of quantization levels, γ is the number of positive (negative) noisy lower bits (quantization levels) of the ADC recorder.

The dynamic range of the stand-alone recorder is determined by the ratio of the maximum input voltage of the ADC to the amplitude of the input signal, determined from expression (2), at a given digitization accuracy.

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$$\begin{aligned} DR &= 20\log\left(u_m / A\right) = \\ &= 20\log\left(u_m \delta / \gamma\Delta\right) = \\ &= 20\log\left(\delta 2^{M-1} / \gamma\right) \end{aligned} \tag{3}$$

When the noise level of the analog part of the measuring channel is much less than the quantum ADC $\gamma = 1$ (quantization noise), then at $M = 16$ and $\delta = 0.05$, $DR = 65$ dB. In the presence of noise of the analog part of the channel, the number of noisy quanta increases, for example, $\gamma = 2$, then at $M = 16$ and $\delta = 0.05$, $DR = 58$ dB.

That is, a stand-alone recorder with an operating frequency band from 2 Hz to 50 kHz and a 16-bit "sigma-delta" ADC number of noisy effective quants $\gamma = 1.6$, $\gamma = U_m/4$, (where U_m - effective noise voltage), can provide a basic dynamic range of the recorder of 60 dB per relative registration error $\delta = 0.05$ (5 %). The use of algorithms for high-frequency (HF) filtering and signal recovery reduces the probability of channel overload, which is equivalent to increasing the effective dynamic range of the recorder.

Consider further the procedure of high-frequency filtering and subsequent recovery of the signal in the computer according to the known transfer function of the filter in the channel of the amplifier signal sensor.

Since real signals are considered, they must satisfy the requirement of causality (physical ability to be realized) [10] $A(t) = 0$ when $t < 0$, that is, the signal of acceleration, velocity, or displacement at the output of the analog-to-digital converter (ADC) is zero at $t < 0$.

We assume that the acceleration signal in the time domain allows the representation in the form of the inverse Fourier transform.

As mentioned above, to increase the dynamic range of the ADC when the signal is amplified, the high-frequency component of the acceleration signal is pre-filtered. The signal at the output of the recorder amplifier has the form [13]

$$A_F(t) = \frac{1}{2\pi}\int_{-\omega_m}^{\omega_m} S(\omega) F_d(\omega) \exp(j\omega t)\, d\omega, \tag{4}$$

where $F_d(\omega)$ is the transmission function of the high-frequency distorting filter. The transfer function of the filter in the hardware implementation of the amplifier in a stand-alone recorder is:

$$\begin{aligned} &F_d(\omega) = (1 + j\omega\tau_2)/(1 + j\omega\tau_1); \\ &x = \tau_2 / \tau_1 = \omega_1 / \omega_2 < 1, \end{aligned} \tag{5}$$

where $0 < \chi < 1$ is the level of signal suppression in the high-frequency region of the spectrum, τ_1, τ_2 are filter constants that determine the characteristic frequencies $\omega_2 = 1/\tau_2$ and $\omega_1 = 1/\tau_1$ on the amplitude-frequency characteristic of the filter.

Next, there should be a procedure for restoring the signal on the spectrum $S_F(\omega)$ obtained by the inverse Fourier transform from the measured acceleration signal

$$\begin{aligned} &A(t) = \frac{1}{2\pi}\int_{-\omega_m}^{\omega_m} \frac{S_F(\omega)}{F_d(\omega)} \exp(j\omega t)\, d\omega; \\ &S_F(\omega) = \int_0^T A_F(t) \exp(-j\omega t)\, dt. \end{aligned} \tag{6}$$

Consider signal recovery as the inverse problem [12], [14].

When restoring the signal (solving the inverse problem), following problems may appear:

- Is there a solution to the problem?
- If there is a solution, is it the only one?
- Is the decision stable, i.e., do small obstacles lead to small changes in the decision?

The presence of a solution. The solution exists and belongs to the class if the conditions are satisfied [11]:

$$S_F(\omega)/F(\omega) = S(\omega) \in L_2(-\infty, \infty)\,. \tag{7}$$

Unity of solution. Assume that at some interval Ω_Δ bounded by points ω^* and ω^{**} on the frequency axis, the transfer function of the filter is zero $F(\omega) \equiv 0$; $\omega^* < \omega < \omega^{**}$, while at this interval $S(\omega) \neq 0$. Then, according to the equality $S_F(\omega) = F(\omega)S(\omega)$ when an arbitrary function $G(\omega)$ equal to zero outside the interval Ω_Δ is added to $S(\omega)$, the type of the measured spectrum $S_{AF}(\omega)$ will not change, and the signal recovery will be satisfied by any function of the form $S(\omega) = S(\omega) + G(\omega)$. Therefore, the recovered signal is determined to the nearest function whose Fourier image is zero outside the frequency range Ω_Δ.

Stability of the decision. The solution has stability if the transfers function $F(\omega) \to 0$ at $\omega \to \infty$ [12], [17].

Consider the accuracy of the initial estimate of the spectrum using FFT [14] and the convergence of the spectrum at $\Delta t \to 0$.

Discrete samples of the acceleration signal obtained with an ideal ADC can be represented as a continuous acceleration signal taken at discrete moments in time

$$A(t_k) = \frac{1}{2\pi}\int_{-\omega_m}^{\omega_m} S(\omega)\exp(j\omega t_k)\,d\omega, \quad t_k = k\Delta t, \tag{8}$$

where Δt is step by time.

The final discrete sample of the acceleration signal is stored and used to analyze the signals and their spectra. Estimation of the acceleration signal spectrum obtained by the FFT of the final discrete implementation of the acceleration signal has the form

$$\breve{S}(\omega_i) = \sum_{k=0}^{N-1} A(t_k)\Delta t\exp(-j\omega_i t_k) = \frac{\Delta t}{2\pi}\int_{-\omega_m}^{\omega_m} S(\omega)K_N(\omega-\omega_i)\,d\omega, \tag{9}$$

where K_N - spectral window function at FFT:

$$K_N(\omega-\omega_i) = \frac{\sin\left((\omega-\omega_i)T/2\right)}{\sin\left((\omega-\omega_i)\Delta t/2\right)} \times \exp\left(j\left((\omega-\omega)(T-\Delta t)/2\right)\right). \tag{10}$$

The error in estimating the spectrum of the output acceleration signal from the final discrete implementation of the acceleration signal is defined as the norm of the difference

$$\Pi_S = \left\|\breve{S}(\omega_i) - S(\omega_i)\right\| = \max_i\left|\breve{S}(\omega_i) - S_T(\omega_i)\right| = \max_i\left|\frac{\Delta t}{2\pi}\int_{-\omega_m}^{\omega_m} S(\omega)K_N(\omega-\omega_i)\,d\omega - S_T(\omega_i)\right|, \quad \forall\omega_i \in [0;\omega_m] \tag{11}$$

where $S_T(\omega_i)$ is the spectrum of the final continuous implementation of the acceleration signal.

We convert the expression for error (10), as shown below

$$\Pi_S = \left\|\frac{\Delta t}{2\pi}\int_{-\omega_m}^{\omega_m} S(\omega) \times \left[\frac{\exp\left(j(\omega-\omega_i)T-1\right)}{\exp\left(j(\omega-\omega_i)\Delta t-1\right)} - \frac{\exp\left(j(\omega-\omega_i)T-1\right)}{j(\omega-\omega_i)\Delta t}\right]d\omega\right\| = \left\|\frac{\Delta t}{2\pi}\sum_{n=-M}^{M}\int_{\omega_n}^{\omega_n+\Delta\omega} S(\omega) \times \left[\frac{\exp\left(j(\omega-\omega_i)T-1\right)}{\exp\left(j(\omega-\omega_i)\Delta t-1\right)} - \frac{\exp\left(j(\omega-\omega_i)T-1\right)}{j(\omega-\omega_i)\Delta t}\right]d\omega\right\| = \left\|\frac{\Delta t}{2\pi}\sum_{n=-M}^{M}\int_{0}^{\Delta\omega} S(\omega+\varepsilon) \times \left[\frac{\exp(j\varepsilon T)-1}{\exp\left(j(\omega_n-\omega_i+\varepsilon)\Delta t\right)-1} - \frac{\exp(j\varepsilon T)-1}{j(\omega-\omega_i+\varepsilon)\Delta t}\right]d\varepsilon\right\|, \tag{12}$$

where $\omega_n = n\Delta\omega$, $M = \omega_m/\Delta\omega$ are the number of samples on the frequency in the informative region of the spectrum of the acceleration signal. At $\Delta\omega\Delta t << 1$ or $N >> 2\pi$, $\omega_m\Delta t \to 0$ and $N\Delta t = T < \infty$ expression for error (11) due to the marginal ratio $1/(exp(j\mu\Delta t) - 1) - 1/j\mu\Delta t = -0{,}5$ at $\mu\Delta t \to 0\forall$, $0 \leq \omega_i \leq \omega_m$ will take the form $\Pi_S \leq 0{,}5\Delta t|A(T) - A(0)|$. From this expression, it follows that under rediscretisation ($\Delta t \to 0$) the error (10) goes to zero, which means that the spectrum obtained by digitization and FFT converges to the spectrum of the final implementation of the original continuous signal.

Next, you need to consider the algorithm and accuracy of recovery of the distorted signal in the recorder.

The filtered signal is fed to the ADC. The readings of the filtered and digitized acceleration signals at discrete moments of time have the form

$$A_F(t_k) = \frac{1}{2\pi}\int_{-\omega_m}^{\omega_m} S(\omega)F_d(\omega)\exp(j\omega t_k)\,d\omega, \quad t_k = k\Delta t. \tag{13}$$

The spectrum of the filtered (distorted) acceleration signal obtained by digitization and FFT,

$$S_F(\omega_i) = \sum_{k=0}^{N-1} A_F(t_k)\Delta t\exp(j\omega t_k) = \frac{\Delta t}{2\pi}\int_{-\omega_m}^{\omega_m} S(\omega)F_d(\omega)K_N(\omega-\omega_i)\,d\omega. \tag{14}$$

Discrete spectrum, which is used to estimate the spectrum and restore the initial acceleration signal

$$\breve{S}_F(\omega_i) = S_F(\omega_i)/F_D(\omega_i),$$

$$F_D(\omega_i) = \begin{cases} F_d(\omega_i), |\omega_i| \le \omega_D/2; \\ F_d(\omega_D - \omega_i), \omega_D/2 \le |\omega_i| \le \omega_D. \end{cases} \quad (15)$$

This definition of the recovery procedure is possible because the transfer function of the filter is not zeroed in the frequency range from 0 to ω_D.

Error in determining the spectrum of the acceleration signal when using the procedure of filtering and subsequent recovery $\forall \omega_i \in [0, \omega_D]$.

$$\begin{aligned} \Pi_{SF} &= \left\| \breve{S}_F(\omega_i) - \breve{S}(\omega_i) \right\| = \\ &= \left\| \frac{\Delta t}{2\pi} \int_{-\omega_m}^{\omega_m} S(\omega) \frac{F_d(\omega)}{F_D(\omega_i)} K_N(\omega - \omega_i) d\omega - \breve{S}_A(\omega_i) \right\| = \\ &= \left\| \sum_{n=-M}^{M} \frac{\Delta t}{2\pi} \int_0^{\Delta\omega} S(\omega_n + \varepsilon) \left[\frac{F_d(\omega_n + \varepsilon)}{F_D(\omega_i)} - 1 \right] \times \right. \\ &\quad \left. \times \frac{\exp\left(j(\omega_n - \omega_i + \varepsilon)T\right) - 1}{\exp\left(j(\omega_n - \omega_i + \varepsilon)\Delta t\right) - 1} d\varepsilon \right\|. \end{aligned} \quad (16)$$

Decomposing the function $F_d(\omega_i + \omega_n - \omega_i + \varepsilon)$ into a Taylor series by degrees $\omega_n - \omega_i + \varepsilon$ and being limited to the first three components and using the condition $|(\omega_n - \omega_i + \varepsilon)\Delta t| < 0{,}1$, we obtain the expression for the absolute error of the spectrum recovery for all $\omega_i \in [0{,}0{,}5\omega_D]$:

$$\begin{aligned} \Pi_{SF} &= \left\| \sum_{p=-P}^{P} \frac{S(\omega_i + p\Delta\omega)}{2\pi F(\omega_i)} \frac{\Delta\omega}{j} \times \right. \\ &\quad \left. \times \left[\frac{dF_d(\omega_i)}{d\omega} + \frac{\Delta\omega\left(p + (\pi - j)/2\pi\right)}{2} \frac{d^2 F_d(\omega_i)}{d\omega^2} \right] \right\|, \end{aligned} \quad (17)$$

where the summation limit $P = 1{,}2{,}3$ is determined by the allowable energy loss in the spectrum of the measured signal and the condition $2\pi P/N < 0{,}1$.

From the analysis of expressions for the error of estimating the spectrum of the initial signal, it is seen that the total error of spectrum recovery consists of the error caused by the use of FFT and the error caused by the distortion of the output signal.

3. Conclusion

The paper presents the basic principles of the construction of portable recorders of vibration and shock signals adapted to modern requirements.

Vibration tests are often unique and non-reproducible (poorly reproducible) tests of products in extreme conditions, which increases the requirements for calibration and parameterization of measuring channels of devices that record information about the nature of product behavior during testing. Therefore, the obtained ratios allow estimating the dynamic range when constructing measuring channels of autonomous recorders during shock tests.

This achieves a dynamic range without switching the gain because the solution to this problem eliminates overload (invalid measurements) and allows you to match the dynamic range of sensors and recording equipment. Accurate measurements are performed for the first time, even when using mixed sensors.

In the course of the research, a method was developed to expand the dynamic range and increase the accuracy of dynamic measurements of shock signals, which in contrast to the previously known differs in that it allows to measure signal switching in the measuring channel; which prevents the impact on the piezoelectric accelerometer of high-frequency vibrations, and prevents the destruction of its sensitive element during shock tests.

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