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# FINDING THE DYNAMIC RANGE OF RECORDERS DURING IMPACT TESTS

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***Abstract*****—***In aircraft construction, when creating samples of new equipment, impact tests are often performed, both of individual components and of the entire product. It requires to introduce 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 impact 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 on board the test product and to ensure the synchronization of the registration of the impact load.*

**Index Terms—**Non-destructive testing; impact tests; measurements; sensitivity; accuracy; external vibrations.

## I. INTRODUCTION

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

When testing objects, there is a need to develop and use small, portable, autonomous recording devices that work directly on the test object under vibration load [3], [4].

Operation of the recorder directly on the tested object in the conditions of vibration loading imposes to the recorder the following special requirements: small dimensions and weight; autonomy; vibration and impact resistance; insensitivity to electromagnetic radiation; wide temperature range. 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 carry out:

- ensuring the autonomy of the recording equipment on board the sample of equipment;
- ensuring synchronization of the course of registration of measuring information;
- storage and transmission of information in a computer with subsequent express-analysis of registered information.

Autonomy is the main property of the registrar, 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 [5], [6].

Operation of the registrar in the independent mode directly on the tested object in the conditions of loading imposes special requirements to the registrar. They are that the recorder must be autonomous, small, highly reliable and have a minimum set of functional nodes in the channel – an amplifier, ADC, microprocessor and storage device, as well as not serviced. 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 registrar 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 a number of properties:

- internal management of all elements;
- automatic transfer from registration mode to standby mode or information issuance mode;

- the ability to program an a priori minimum set of basic parameters of the registrar.
- To ensure compliance with the requirements for the registrar, it is necessary to use the following principles and methods of building registrars:
- 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.

## II. Problem Statement

Impact tests are often one-off, destructive tests of products, which significantly increases the requirements for calibration and parameterization of output channels. 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. A priori information about the various impact effects has significant differences, as it is obtained on the basis of 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 impact can be accompanied by high-frequency mechanical perturbations, which also leads 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.

## III. Subject & Methods

In the development of stand-alone recorders, the problem of providing a dynamic range of the measuring channel of the recorder with a given accuracy of registration of the vibration signal by non-switching method, i.e. without switching the gain and changing the frequency characteristics of the channel [7].

Adjusting the gain and frequency characteristics of the channel in a stand-alone recorder is very difficult (and in the process of testing and 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), 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 [15]. 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 was less than the linearity range of the accelerometer with a margin of about 30% [8].

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 to coordinate the dynamic range of sensors and recording equipment. Accurate measurement is obtained from the first time, 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 [9], the true dynamic range of the ADC determines the relationship between the magnitude of the converted load on the RMS (root mean square) of the total noise component in digitization systems.

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

where $\sigma_\Sigma$ is RMS 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 [12] by an expression that does not include the error of signal measurement, and for impact 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 impact 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)

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

where $\Delta$ is the step of quantizing the input signal by voltage, $u_m$ is maximum ADC input voltage, $A$ is impact pulse amplitude (input signal to ADC), $M$ is number of quantization levels, $\gamma$ 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.

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

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

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, $DR$ = 65dB. 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, $DR$ = 58dB.

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 $\gamma = U_m/\Delta$ (where $U_m$ is the effective noise voltage), is able to 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) [9] $A(t) = 0$ when $t$ < 0, that is, the signal of acceleration, velocity or displacement at the output of the 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

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

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:

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

where $0 < \chi < 1$ the level of signal suppression in the high frequency region of the spectrum, $\tau_1, \tau_2$ 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

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

Consider signal recovery as the inverse problem [11], [13].

When restoring the signal (solving the inverse problem) there are appearing such a problems as:

- 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.

Existence of a solution. The solution exists and belongs to the class if the conditions are satisfied [10]:

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

Unity of solution. Assume that at some interval $\Omega_\Delta$ bounded by points $\omega^*$ and $\omega^{**}$ 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 added to $S(\omega)$ an arbitrary function $G(\omega)$ in equal to zero outside the interval $\Omega_\Delta$, 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 any function whose Fourier image is zero outside the frequency range $\Omega_\Delta$.

Stability of the decision. The solution has stability if the transfer function $F(\omega) \to 0$ at $\omega \to \infty$ [11].

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 of 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 $\Delta t$ 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

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

where $K_N$ is the spectral window function at FFT:

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

is the spectral window function at FFT.

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 difference

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

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

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

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 $\Delta\omega\Delta t \ll 1$ or $N \gg 2\pi$, $\omega_m \Delta t \to 0$ 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 redescretisation $(\Delta t \to 0)$ 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

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

$$t_k = k\Delta t.$$

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

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

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

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 $\omega_D$.

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

$$\Pi_{SF} = \left\|\tilde{S}_F(\omega_i) - \tilde{S}(\omega_i)\right\| = \left\|\frac{\Delta t}{2\pi}\int_{-\omega_m}^{\omega_m} S(\omega)\frac{F_d(\omega)}{F_D(\omega_i)}K_N(\omega-\omega_i)\,d\omega - \tilde{S}_A(\omega_i)\right\|$$
$$= \left\|\sum_{n=-M}^{M}\frac{\Delta t}{2\pi}\int_0^{\Delta\omega} S(\omega_n+\varepsilon)\left[\frac{F_d(\omega_n+\varepsilon)}{F_D(\omega_i)} - 1\right]\cdot\frac{\exp\big(j(\omega_n-\omega_i+\varepsilon)T\big)-1}{\exp\big(j(\omega_n-\omega_i+\varepsilon)\Delta t\big)-1}\,d\varepsilon\right\|. \tag{16}$$

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 $\omega_i \in [0, 0.5\omega_D]$:

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

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 $2\pi P/N < 0.1$.

## VI. CONCLUSION

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 to estimate the dynamic range when constructing measuring channels of autonomous recorders during impact tests.

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**А. П. Стахова, С. Л. Макаровський. Знаходження динамічного діапазону реєстраторів при ударних випробуваннях**

В авіабудуванні при створенні зразків нової техніки часто проводять ударні випробування як окремих вузлів, так і всього виробу. Це вимагає впровадження у виробництво приладів неруйнівного контролю, що є одним із найважливіших чинників прискорення науково-технічного прогресу, підвищення якості та конкурентоспроможності продукції, що випускається. При застосуванні сучасних засобів неруйнівного контролю, постає проблема їх захисту від зовнішніх вібрацій, які впливають на чутливість, точність і надійність високоточних вимірювань. У таких випадках перетворення вимірювальної інформації під час потужних вібраційних і ударних випробувань, як правило, здійснюється п'єзоелектричними датчиками прискорення. Також для проведення випробувань на удар необхідно розробити та використовувати автономні реєстратори. Основними вимогами до цих реєстраторів є забезпечення автономності та працездатності реєстратора на борту випробовуваного виробу та забезпечення синхронізації реєстрації ударного навантаження.

**Ключові слова:** неруйнівний контроль; випробування на удар; вимірювання; чутливість; точність; зовнішні вібрації.

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**А. П. Стахова, С, Л. Макаровский. Определение динамического диапазона регистраторов при испытаниях на удар**

В авиастроении при создании образцов новой техники часто проводят ударные испытания как отдельных узлов, так и всего изделия. Это требует внедрения в производство приборов неразрушающего контроля, что является одним из важнейших факторов ускорения научно-технического прогресса, повышения качества и конкурентоспособности выпускаемой продукции. При применении современных средств неразрушающего контроля возникает проблема их защиты от внешних вибраций, влияющих на чувствительность, точность и достоверность высокоточных измерений. В таких случаях преобразование измерительной информации при мощных вибрационных и ударных испытаниях, как правило, осуществляется пьезоэлектрическими датчиками ускорения. Также для проведения ударных испытаний необходимо разработать и использовать автономные регистраторы. Основными требованиями к этим регистраторам являются обеспечение автономности и работоспособности регистратора на борту испытуемого изделия и обеспечение синхронизации регистрации ударной нагрузки.

**Ключевые слова:** неразрушающий контроль; испытания на удар; измерения; чувствительность; точность; внешние вибрации.

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