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Translation

Instruments and Systems for Measuring Vibration, Noise and Shock

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INSTRUMENTS AND SYSTEMS FOR MEASURING VIBRATION, NOISE AND SHOCK

Moscow PRIBORY I SISTEMY DLYA IZMERENIYA VIBRATSII, SHUMA I UDARA in Russian 1978 signed to press 1 Aug 78 pp 112-117, 143-196, 232-239

Excerpts from book edited by V. V. Klyuyev, "Mashinostroyeniye" Publishers, 440 pages, 30,000 copies

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CHAPTER 11. BALANCING EQUIPMENT

The Main Characteristics of the Balancing Process and Balancing Equipment

[Excerpt] The major cause of vibration in roating mechanism (rotors) is their lack of balance, which arises during the redistribution of masses about the periphery and about the length, something which causes a displacement of the main center axis of inertia of the rotor with respect to its axis of rotation. Depending on the mutual position of these axes, distinctions are drawn between static, dynamic and mixed disbalances.

A disbalance is termed static if the vibration vectors at both supports are equal. In this case, the center of gravity of the rotor is shifted from the axis of rotation by an amount ε. The centrifugal imbalancing force is $P = M\omega^2\varepsilon$, where M is the mass of the rotor; ω is the angular rotational speed; ε is the displacement of the center of gravity with respect to the axis of rotation (the eccentricity).

A disbalance is called dynamic if the vibration vectors are equal in terms of absolute value and are out of phase. If the vibration vectors are not equal in terms of absolute value and phase, then the disbalance is called mixed.

In the majority of cases, unbalanced rotors have a mixed disbalance.

We shall consider the static balancing of a disk, rotating at a speed considerably lower than the first critical frequency.

The balancing is accomplished in the following sequence. During the initial start of the disk, the vibration vector $\bar{A}_0$ is measured. Then a test load P_π is placed on the rotor and during the second run-up, the vector $\bar{A}_{01}$. Thus, the vibrations are caused by the sum of the centrifugal forces of the disk and the test load. Then the vibration vector $\bar{A}_\pi$, caused by the test load, will be $\bar{A}_\pi = \bar{A}_{01} - \bar{A}_0$. The balancing load is

$$P_{\text{б}} = \frac{P_{\text{п}}}{A_{\text{п}}} A_0.$$

Its setting angle $\phi_{\text{б}}$ is determined from the vector diagram. Consequently, to achieve balance, instead of the load P_π, it is necessary to take $P_{\text{б}}$, rotate it through the angle $\phi_{\text{б}}$ and position it at the same radius. If the setting radius of the balancing load $r_{\text{б}}$ differs from the setting radius of the test load r_π, then $P_{\text{б}}$ can be computed from the from the formula:

$$P_{\text{б}} = \frac{r_{\text{п}}}{r_{\text{б}}} \frac{A_0}{A_{\text{п}}} P_0.$$

In the case of static balancing of the given rotor, the balance loads are placed on both sides of the rotor. If their setting radii are equal for both sides, then the loads are defined by the expressions:

$$P_{1\text{б}} + P_{2\text{б}} = P_{\text{б}}; \quad P_{1\text{б}} = P_{2\text{б}}.$$

If $r_1 \neq r_2$, then the loads must be corrected in accordance with the formulas

$$P_{1\text{б}} r_1 = P_{2\text{б}} r_2; \quad P_{1\text{б}} + P_{2\text{б}} \frac{r_2}{r_1} = P_{\text{б}}.$$

In the case of a dynamic disbalance, the balancing loads are computed in a similar manner, but $P_{1\text{б}}$ and $P_{2\text{б}}$ are placed on both sides of the rotor.

In the case of mixed disbalance, the balancing can be accomplished by dividing the vectors into static and dynamic vectors. It can be seen in the vector diagram (Figure 3) that the vectors $\bar{A}_{\text{oc}}$ and $\bar{A}_{\text{oд}}$ are equal to half of the sum and half of the difference of the vibration vectors $\bar{A}_{01}$ and $\bar{A}_{02}$:

$$\bar{A}_{\text{oc}} = \frac{\bar{A}_{01} + \bar{A}_{02}}{2}; \quad \bar{A}_{\text{oд}} = \frac{\bar{A}_{01} - \bar{A}_{02}}{2},$$

where $\bar{A}_{01}$ is the vibration vector at the first support; $\bar{A}_{02}$ is the vibration vector at the second support.

The vector $\bar{A}_{oc}$ determines the static imbalance of the rotor, while $A_{o\text{д}}$ determines the dynamic imbalance.

In this case, the rotor can be balanced by separately eliminating the static and dynamic imbalances in a manner similar to the preceding one.

The method of computing the balancing loads by means of complex sensitivities has become widespread. This method is most widely employed in the balancing coupled rotor systems, i.e., where the number of supports and balancing planes is greater than two.

The initial vibration vectors of a rotor have values of $\bar{A}_{01}$ and $\bar{A}_{02}$. Prior to run-up, a test load P_{π} is placed on the first balance plane of the rotor. During the first run-up, the vibration vectors $\bar{A}_{11}$ and $\bar{A}_{12}$ are measured and the following coefficients are computed:

$$\bar{a}_{11} = \frac{\bar{A}_{11} - \bar{A}_{01}}{P_{\pi 1}}; \quad \bar{a}_{21} = \frac{\bar{A}_{12} - \bar{A}_{02}}{P_{\pi 2}},$$

where a_{11} and a_{21} are the relative changes in the vibration vectors at the rotor supports when the test load $P_{\pi 1}$ is mounted on the first balancing plane.

Prior to the second run-up, the load $P_{\pi 1}$ is removed and the load $P_{\pi 2}$ is placed in the second balancing plane of the rotor. During the second run-up, the vibration vectors $\bar{A}_{21}$ and $\bar{A}_{22}$ are measured, and the following coefficients are calculated:

$$\bar{a}_{12} = \frac{\bar{A}_{21} - \bar{A}_{01}}{P_{\pi 2}}; \quad \bar{a}_{22} = \frac{\bar{A}_{22} - \bar{A}_{02}}{P_{\pi 2}},$$

where $\bar{a}_{12}$ and $\bar{a}_{22}$ are the relative changes in the vibration vectors at the rotor supports when the test load is placed in the second balance plane.

The coefficients a are called the complex sensitivities and express the change in the vibration vector with a change in the disbalance per unit weight as well as when it is positioned at the origin for the readout of the angle of the vectors ($\phi = 0$). These coefficients do not depend on the test load.

Depending on the angular position, the balancing loads are determined from the system of equations:

$$\bar{P}_1\bar{a}_{11} + \bar{P}_2\bar{a}_{12} + \bar{A}_{01} = 0;$$
$$\bar{P}_1\bar{a}_{21} + \bar{P}_2\bar{a}_{22} + \bar{A}_{02} = 0.$$

In the case of the balancing of a coupled system of rotors with n supports and planes, the number of complex sensitivities is n^2. It is necessary to make n test runs to determine them.

The balancing loads are found from a system of n equations:

$$\begin{aligned}
&\bar{P}_1\bar{a}_{11} + \bar{P}_2\bar{a}_{12} + \ldots + \bar{P}_n\bar{a}_{1n} + \bar{A}_{01} = 0;\\
&\bar{P}_1\bar{a}_{21} + \bar{P}_2\bar{a}_{22} + \ldots + \bar{P}_n\bar{a}_{2n} + \bar{A}_{02} = 0;\\
&\cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\\
&\bar{P}_1\bar{a}_{n1} + \bar{P}_2\bar{a}_{n2} + \ldots + \bar{P}_n\bar{a}_{nn} + \bar{A}_{on} = 0.
\end{aligned}$$

Such a system of equations is solved by means of special computer programs or using specialized computers.

The problem is complicated in the case of vibration at frequencies differing from the rotational frequency, i.e., in the presence of interference caused by roller bearings, nonuniformity of the electromagnetic field, etc., as well as noise transmitted through the foundation and from other mechanisms.

The main function of balancing equipment is the measurement of the parameters of oscillations caused a disbalance in the presence of a high interference level.

The following major parameters of oscillations are measured using balancing equipment: the amplitude or peak to peak value of a vibrational displacement; the relative phase shift.

Balancing equipment has filtering units for isolating oscillations which cause a disbalance from the entire spectrum of vibrational frequencies of the rotating rotors. Additionally, units for measuring the oscillation frequency, the spectral analysis of the vibrational speed parameters, the vibrational acceleration, etc., can be included in the equipment.

Balancing equipment can be composed of instruments intended for vibrational measurements. By way of example, we shall consider the unit shown in Figure 1. The rotor being balanced 1 rotates in bearings 2. An induction vibrational transducer 3 is rigidly secured to the bearing, while the rotor of the reference generator 9 is rigidly tied to the rotor being balanced. The reference signal generator generates a sinusoidal voltage or pulses, having a repetition rate equal to the rotor frequency.

The vibrational transducer picks up the bearing oscillations and generates a voltage proportional to the vibrational speed of the spectral components. If the spectrum of the oscillations falls in a range in which the absolute value and phase of the transmission factor of the seismic system do not depend on the frequency, then the voltage at the output of the vibration transducer is:

$$U(t) = B\sum_{i=0}^{n}\omega_i A_i \cos(\omega_i t + \varphi_i),$$

where B is the transmission factor; A_i and ϕ_i are the amplitude and phase of the vibrational displacement of the spectrum component at a frequency of ω_i.

Analog integrating 4 is used to convert the signal proportional to the vibrational speed to a signal which is proportional to the vibrational displacement. If it is assumed that the analog integrator is ideal in a range of frequencies from ω_0 to ω_n, then its output voltage is:

$$U_1(t) = \int U(t)\,dt = \frac{B}{\tau} \sum_{i=0}^{n} A_i \sin(\omega_i t + \varphi_i),$$

where τ is the integrator time constant, i.e., the signal level does not depend on the frequency of the components of the spectrum.

The block of bandpass filters 5 serves to isolate a component A_0 with a frequency of ω_0 equal to the rotational frequency from the spectrum. If the filter is ideal, if the transfer coefficients at the frequency ω_0 are equal to unity, and are zero at rotational frequencies other than ω_0, and also do not introduce a phase shift at ω_0, then a single-harmonic signal at the frequency ω_0 is produced at its output:

$$U_2(t) = B_1 A_0 \sin(\omega_0 t + \varphi_0),$$

where B_1 is the overall conversion factor (of the vibrational transducer--integrator--filter).

The amplitude of the voltage $U_2(t)$, which is proportional to the amplitude of the oscillations A_0, is measured with voltmeter 6; the frequency of the oscillations ω_0 is read out on frequency meter 7, and the waveform of the process is monitored on oscilloscope 10.

Phase meter 8 serves for the measurement of the phase shift between $U_2(t)$ and the voltage picked off from thereference signal generator 9. Selsyns, rotating transformers, pulse sensors and other devices which generate signals, the frequency of which coincides with the rotational frequency, can serve as the reference signal generator.

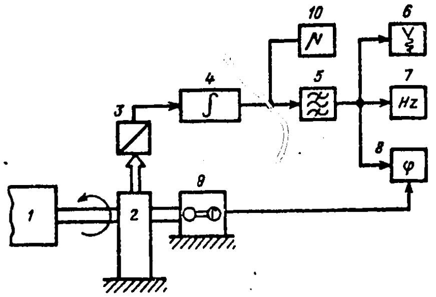


Figure 1.

A block diagram of a standard unit for dynamic balancing.

In the system considered here, the amplitude and phase-frequency response of the seismic system of the vibrational transducer, the integrator, the filters and all of the measurement instruments have been idealized. Practically all of the devices introduce considerable errors, especially when making measurements at low frequencies. When designing vibrational measurement equipment, primary attention is devoted to the reduction of of amplitude frequency response errors. In balancing equipment, the amplitude and phase freqeuncy response errors are of the same sign.

The octave and third-octave filters used in vibrational measurements have an impermissibly wide passband for balancing equipment, while narrow band filters have large phase-frequency errors, which are especially marked in the case of an unstable rotational frequency. If the filters are eliminated, then small amplitude and phase-frequency errors are introduced by the seismic system of the vibrational transducer and the integrator. The transmission coefficients are determined from the formulas:

$$v_c = \frac{x^2}{\sqrt{(1-x^2)^2 + 4\beta^2 x^2}};$$

$$\varphi_c = \operatorname{arctg}\frac{2\beta x}{1-x^2},$$

where v_c is the absolute value of the frequency characteristics; ϕ_c is the phase shift in the seismic system; 2β is the damping factor; $x = f/f_p$ is the relative frequency; f is the vibration frequency; and f_p is the frequency of the first resonance of the seismic system.

In the lower portion of the measurement frequency range, the errors depend on x and 2β. The amplitude-frequency error is

$$\delta = \frac{x^2}{\sqrt{(1-x^2) + 4\beta^2 x^2}} - 1$$

and falls off with an increase in β to 0.5–0.55 of the critical attenuation. With a further increase in β (> 0.55), the error begins to rise, but with an increase in the damping factor, the phase-frequency error increases, since the phase shift is directly proportional to β. For this reason, in balancing instruments, the increase in β is limited by the permissible phase-frequency errors.

In vibrationa measurement equipment, the rise in the amplitude-frequency response of the vibration transducer at low frequencies, in the case of inadequate damping in its seismic system, is compensated by means of an integrating section. In this procedure for reducing the amplitude-frequency errors, the phase-frequency errors in the lower portion of the frequency range likewise increase. For this reason, special vibrational transducers and integrators have been designed for balancing equipment.

Analog integrators designed around microelectronic operational amplifiers have become the most widespread in contemporary equipment.

The basic schematics of analog integrators are shown in Figures 2a and b. The supplemental components R_{oc} and C_{oc} are introduced to limit the direct current gains of the operational amplifiers, Y.

Analog integrators frequently perform the function of signal amplifiers, for signal picked off from the transducer. The schematic of an analog amplifier-integrator is shown in FIgure 2c.

All analog integrators have a comparatively slow operating speed. Depending on the requisite integration precision, the integration time amounts to tens and hundreds of input signal periods. Moreover, analog integrators have a limited range on the downside (the lower integration frequency amounts to units, and more rarely, tenths of a Hertz). For this reason, when high speed is required in balancing instruments (for example, to measure the vibration in the case of transient processes, for multiple point instruments), analog-digital, digital and number-pulse integration circuits are finding ever increasing application. The frequency range of integrators is practically unlimited on the downside, and for this reason, they can have an integration time equal to one period, and in some cases, even half or one quarter of a period.

In balancing equipment, the useful signal is segregated from the spectrum of oscillations by special filter devices. In the majority of cases, special electrical filters, as well as multiplier circuits, are used as such devices.

Balancing equipment can be conditionally broken down into three groups:

1. Equipment with electrical filters;
2. Equipment with selective multipliers;
3. Equipment with combination selective devices.

CHAPTER 12. VIBRATION TEST SYSTEMS

[Excerpts] Contemporary vibration test systems, the action of which is based on the utilization of the test methods considered here, take the form of complex sets, which primarily include subsystems for setting, reproducing, controlling and measuring, and analyzing and recording vibration parameters.

The main component of test systems is the vibrator: the driving element which is intended for reproducing the specified oscillations. Depending on the operational principle of the vibrator, various methods are used in the system to set the test mode. Electrodynamic, electrohydraulic and mechanical vibrators, which were described in Chapter 14, have become the most widespread in practice. The first two types of vibrators are employed in vibration systems which realize all of the modern test procedures. In this case, electrical signal generators are employed as the setting unit. Electrodynamic vibrators make it possible to generate oscillations at higher frequencies (5-10,000 Hz) than electrohydraulic ones (0-1,000 Hz). Mechanical vibrators are employed in systems intended for testing using the method of fixed frequencies.

The major drawback to all types of vibrators is the dependence of their transfer function on the frequency and load, something which substantially

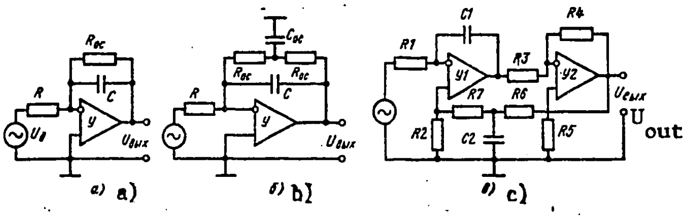


Figure 2. Basic schematics of analog integrators.

$R_{oc} = R_{feedback}$.

complicates the task of reproducing specified vibration parameters during tests in a wide range of frequencies. For this reason, to realize any test procedure, special methods are required to compensate for changes in the transfer function with changes in the frequency and loads.

Systems for Tests Using Harmonic Effects

Test Systems Using the Method of Fixed Frequencies. A block diagram of a vibrational system for performing tests using fixed harmonic vibration modes and the electrodynamic excitation principle is shown in Figure 7. It contains a master oscillator 1, the sinusoidal voltage at a specified frequency and amplitude from which is fed to power amplifier 2 and the moving coil of vibrator 3, in which the electrical oscillations are converted to mechanical ones. Using masurement transducer 4, matching amplifier 5 and secondary instrument 6, the specified oscillation level is monitored. When changing from one frequency to another, the level of the oscillations is set by adjusting the voltage of the master oscillator.

Conventional RC oscillators (more rarely, LC oscillators), operating in a wide frequency range (5-10,000 Hz and more), are as a rule used as the master oscillator. The basic requirements which are placed on the oscillator are nonlinear distortions of less than 1 percent, a frequency and amplitude stability of 3 to 5 percent for 8 hours of continuous operation and a frequency scale graduation error of 0.02 f ± 1 Hz. These requirements are the result of the need to reproduce sinusoidal oscillations at specified frequencies, set in accordance with the test program (primarily at the resonant frequencies of the product) for an extended length of time.

The power amplifier is a conventional amplifier, in the final stages of which high power vacuum tubes or transistors are used (recently, circuits designed around thyratrons have appeared). The power of the amplifiers used in vibrational test systems, needed to generate the traction forces of the vibrator ranging from tens to hundreds of thousands of Newtons, fall in a range of tens of watts to hundreds of kilowatts. The load on the amplifiers is the complex impedance of the moving coil of the vibrator, which as a rule is a low impedance and substantially depends on the frequency.

The basic requirements which are placed on modern power amplifiers are: nonlinear distortions of less than 3-5 percent when delivering the requisite power in the working frequency range; the capability of extended continuous operation for 8 hours; operational stability when the load is dropped; a dynamic range on the order of 60 dB and a low noise level (a signal to noise ratio of ≥ 50 dB).

Electrodynamic vibrators serve as the actuating element, which generate a pushing force of up to hundreds of thousands of Newtons with a load lifting capability of up to hundreds of kilograms in a frequency range of from units of hertz to kilohertz and oscillation amplitudes of ≥ 1,000 m/sec^2.

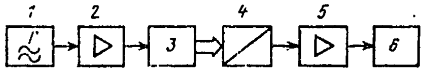


Figure 7. Block diagram for a test system using the method of fixed frequencies with electrodynamic excitation:

Key:
1. Master oscillator;
2. Power amplifier;
3. Vibrator;
4. Vibrational transducer;
5. Matching amplifier;
6. Meter.

Vibration test systems, intended for fixed frequency test procedures, as a rule, are made in the form of cabinets. The control and monitor system is housed in one of the cabinets, the individual units of which (for the measrement of the vibration parameters, the monitoring of the operational modes, the master oscillator, the preamplifier, the power supply of the magnetization coils) are made removable. The power amplifier with the output transformer (in high power amplifiers, more than 3,000 VA, the output transformer is located outside the cabinet) is housed in another cabinet. The adjustement, monitor and signalling controls are positioned on the front panel. There is electromechanical interlocking in the doors of the cabinets.

The technical characteristics of the most widespread modern vibration test systems with electrodynamic exciters in our country and abroad are listed in Table 1.

In vibration test systems, the action of which is based on hydraulic excitation of the oscillations, two methods can be used to generate the specified oscillations: electrical and mechanical. The mechanical method of generating the set oscillations is the simplest. It allows for the production of only harmonic oscillations. As a rule, hydraulic pulsators are used as exciters of the oscillations.

Vibration test systems with hydraulic pulsators permit the generation of alternating forces of $<10^6$ N with vibration amplitudes of <25 mm in a frequency range of <100 Hz. The most widespread models are those of the following companies: "Losenghausen" (FRG), MAN (FRG), "Rail" (US), "Tokio-Koki" (Japan) and "Werkstoffpruefmashinen" (GDR).

A distinctive feature of the electrical method of generating oscillations is the capability of producing oscillations of any waveform with the corresponding circuit complexity of the master and control units of the system. In this case, electrohydraulic vibrators are used as the exciters.

Shown in Figure 8 is a typical block diagram of a testing system using the method of fixed frequencies for the electrical method of generating specified oscillations in a hydraulic vibrator.

The signal from master oscillator 1 and the DC voltage from the zero set position control unit 11 for the moving part of the hydraulic vibrator is fed to adder 2. The composite signal, following amplification is fed to electromechanical transducer 4, in which the electrical oscillations are converted to mechanical ones. The actuating element of the transducer is rigidly coupled to the control slide valve of the first stage of a two-stage (preliminary hydraulic amplifier) of servovalve 5, which converts the mechanical oscillations into proportional changes in the flow of a liquid, amplified by the second stage (a hydraulic power amplifier) of the servovalve. The fluid in the servovalve is fed under pressure from the hydraulic supply unit 8. The force of the fluid is transmitted to the piston actuating mechanism of hydraulic vibrator 6, as well as to the product being tested 7, which is secured to the vibrator table. The specified test mode is monitored by means of measurement transducer 9 (displacement, speed or acceleration) and meter 10.

The major units of the system are the master oscillator, the electrohydraulic vibrator and the hydraulic power source.

A conventional infralow frequency generator is used as the master oscillator, for example, an NGPK-3. The rate of travel of the vibrator table is proportional to the flow of fluid and changes in accordance with the variations in the electrical signal from the master oscillator. Positional and velocity feedback permit the stabilization of the excited parameters.

The electronic units of the system (the oscillator, amplifiers, monitor and control instruments, the devices for observing the level and waveform of the vibrations, switching and interlocked devices, etc.) are usually located on a desk type control panel or (the "Feyri" Company, England) or a control console (the "MB Electronics Company US).

TABLE 1

Technical Characteristics of Vibration Test Systems with Electrodynamic Exciters

Тип системы	Тип вибратора	Тип усилителя мощности	Диапазон частот, Гц	Выталкивающая сила, Н	Выходная мощность, кВ·А	Номинальное ускорение, м/с²	Максимальное перемещение, мм	Максимальная масса, кг	Направление колебаний	Потребляемая мощность, кВ·А
(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)	(J)	(K)
СССР USSR										
ВЭДС-10А	ВЭД-10А	СУПВ-0,1А	5--5000	100	0,1	160	6	1,9	Вертикальное или горизонтальное Vertical or Horizontal	0,7
ВЭДС-100А	ВЭД-100А	УПВ-1,5А		1000	1,5	400	7,5	22		4,5
ВЭДС-200А ВЭДС-200В	ВЭД-200А ВЭД-200Б			2000		400 650	12,5 7,5	45 22		6,0 6,6
ВЭДС-400А ВЭДС-400В	ВЭД-400А ВЭД-400Б	УПВ-3,0		4000	3,0	400 750	12,5	90		19,0 13,0
ВЭДС-900	ВЭД-900	УПВ-10 UPV-10		9000	10,0	820		50		40,0
ВЭДС-1500 VEDS-1500	ВЭД-1500 VED-1500		5–2000	15000		500	6,0	300		42,0
«Дерритрон», Англия "Derritron", England										
Серия VP VP Series	VP-2	25WT	1,5–2000	11,1	0,025	620	2,54	—	Вертикальное Vertical	—
	VP-3	25WT		44,5		170				
		TA120		89,0	0,12	330				
	VP-4	TA120	5–7000	133		315	6,35			
	VP-4B	TA300		222	0,3	525				
	VP-30	TA300		890		400	12,5		Vertical or Horizontal Вертикальное или горизонтальное	
		TA600		1245	0,6	560				
		TA1500		2224	1.5	1000				
	VP-85	TW1500	5–5000	4003		630				
		TW3000		5560	3,0	880				
		TW6000		7561	6,0	1000				
	VP-180	TW6000		8674		885				

Key: A. Type of system;
B. Type of vibrator;
C. Type of power amplifier;
D. Frequency range, Hz;
E. Ejection force, newtons;
F. Output power, KVA;
G. Nominal acceleration, m/sec^2;
H. Maximum travel, mm;
I. Maximum weight, kg;
J. Direction of the vibrations;
K. Power consumption KVA.

TABLE 1, continued:

(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)	(J)	(K)
VP Series	VP-180L	TW12000		12 232		1000				
	VP-400M	TW12000		17 792	12,0					
	VP-600M	TW12000	5–3000	21 128		750				
		TW24000		31 136	24,0	1000				
		36KWLF		37 008	36,0					
	VP-1500	36KWLF	5–6000	53 376		870				
		72KWLF		75 616	72,0	1000				
«Линг», Англия "Ling", England										
100	100	TPO-20	1,5–2000	8,8	0,02	1280	2,5		Вертикальное Vertical	0,056
200	200	TPO-20	1,5–13 000	27		1320	5,0	—		
400	400–98	TPO-100	1,5–9000	98	0,1	490	17,6			0,225
400	400-178	TPO-300		178	0,3	786				0,650
625	625-820			820		315	8,8		Вертикальное или горизонтальное Vertical or Horizontal	
625	625-1550	TPO-1,0	1,5–5000	1550	1,0	600				3,5
710L	710L	TPO-2,0		3130	2,0	882	12,5	28		4,0
805	805	TPO-12/17		13 320	12,0	1200	12,7	—		34,0
825	825			26 600	30,0			—		
851	851	PP30/40		18 140	22,5	1000	12,0	170		—
951	951			39 800				389		
960	960		5–3000	54 600	30,0					70,0
961	961	PP70/120		66 600		980	12,7	—		140,0
962	962			77 500	75,0					
340	—	—	5–2000	12 000	—	1000				—

TABLE 1, continued:

Тип системы	Тип вибратора	Тип усилителя мощности	Диапазон частот, Гц	Выталкивающая сила, Н	Выходная мощность, кВ·А	Номинальное ускорение, м/с²	Максимальное перемещение, мм	Максимальная масса, кг	Направление колебаний	Потребляемая мощность, кВ·А
(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)	(J)	(K)
«Чинкен», Япония "Chinken", Japan										
G-0190	G21-190	G11-005	5–3000	8900	5,0	1000	12,5	—		24.0
G-0215	G21-215	G11-010		15 000	10,0					43.0
G-0225	G21-232	G11-120	5–2500	25 000	20,0					74.0
G-0232		G12-035		32 000	35,0					120.0
G-0250	G21-263		5–2000	50 000						
G-0263		G12-065		63 000	65,0					200.0
G-0310	G21-313	G12-085	5–1800	100 000	85,0					280.0
G-0313		G12-130		130 000	130,0					400.0
G-0320	G21-320	G12-150	5–1600	200 000	150,0	800				490.0
G-7225	G27-225	G12-035	5–2500	25 000	35.0	2000				110.0
G-7250	G27-250	G12-065	5–2000	50 000	65,0					119.0
«IMV LAB CO, LTD», Япония Japan										
VS-3202Д	VE-3202	VA-ST0,6	5–5000	1200	0,6	710	12,5	70	Вертикальное или горизонтальное Vertical or Horizontal	4.0
VS-3202		VA-ST1,0		1700	1,0	1000		120		5.0
VS-3202H		VA-ST1,5		1900	1,5			70		6.0
VS-3203Д	VE-3203	VA-ST1,0	5–4000	2500	1,0	930		120		
VS-3203		VA-ST1,5		3000	1,5	1000				7.0
VS-3203H		VA-ST3,0		3500	3,0					11.0
VS-3204Д		VA-ST1,5		3500	1,5	660				9.0

TABLE 1, continued:

(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)	(J)	(K)
VS-3204	VE-3204	VA-ST3,0	5–3500	5000	3,0	1000	12,5	200	Вертикальное или горизонтальное Vertical or Horizontal	12,0
VS-3204H		VA-ST5,0		6300	5,0					17,0
VS-3204ХД	VE-3204X	VA-ST1,5	5–3800	5000	1,5					22,0
VS-3204X		VA-ST3,0		7000	3,0	1400				25,0
VS-3204XC		VA-ST5,0		9000	5,0	1800				30,0
VS-3205Д	VE-3205	VA-ST3,0	5–3000	7000	3,0	560		300		28,0
VS-3205		VA-ST5,0		9000	5,0	720		500		33,0
VS-3205H	VE-3205H	VA-ST10		1500	10,0	1000				47,0
VS-3205SД	VE-3205S	VA-ST12	5–2500	20 000	12,0	870				60,0
VS-3205S		VA-VT20		25 000	20,0					80,0
VS-3205SH		VA-VT35		31 500	35,0	1000				100,0
VS-3206	VE-3206			50 000				1000		140,0
VS-3206H		VA-VT65		63 000	65,0					200,0
VS-3207	VE-3207	VA-VT75	5–2000	100 000	75,0			2000		260,0
VS-3207H		VA-VT100		125 000	100,0					320,0
VS-3208	VE-3208	VA-VT150	5–1800	200 000	150,0	800		4000		470,0
VS-3208H		VA-VT250		250 000	250,0					700,0
VS-3209	VE-3209		5–1500	315 000		700		6000		750,0
VS-3209H		VA-VT400		400 000	400,0					1100,0
«Аказн», Япония										
ASE-12	ASE-12	ASB-22V	3–10 000	500	—	700	7,5	10	—	1,5
ASE-21V	ASE-21V		5–3500	700		420		30		2,0
ASE-32V	ASE-32S	ASB-32V	5–5000	1400		800	10,0	50		3,0
ASE-32S				1800		1000				
ASE-42SB	ASE-42V	ASB-42V	5–4000	2000		800		100		4,5
ASE-42V				3000		1200				
ASE-42S	ASE-42S	ASB-43		4250		1000	12,5	200		10,0
ASE-52	ASE-52A	ASB-53		6000		670				17,0
ASE-52A		ASB-72B		9000		1000				30,0

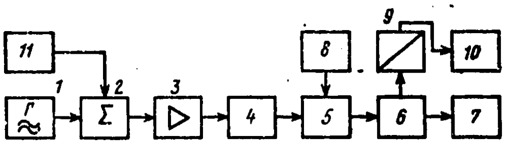


Figure 8. Block diagram of a system for tests using the method of fixed frequencies with hydraulic excitation.

Key: 1. Master oscillator;
2. Adder;
3. Amplifier;
4. Electromechanical transducer;
5. Servovalve;
6. Hydraulic vibrator;
7. Product being tested;
8. Hydraulic supply unit;
9. Vibration trnsducer;
10. Measurement instrument;
11. Control unit.

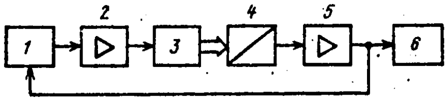


Figure 9. Block diagram of a system for harmonic vibration tests using the sweep frequency method.

Key: 1. Master unit;
2. Power amplifier;
3. Vibrator;
4. Vibrational transducer;
5. Matching amplifier;
6. Measurement instrument.

The electrohydraulic vibration systems of the "MB Electronics" (US) and "Douti Rotol" and "Feyri" Companies (England) have become the most widespread.

Modern electrical hydraulic vibration systems make it possible to perform tests with an expulsive force of $45 \cdot 10^4$ N, an amplitude of the vibrations from fractions to hundreds of millimeters and an acceleration of $< 10^3$ m/sec^2 in a frequency range of 0-150 Hz. The leading companies produce various hydraulic test systems, which differ primarily in their technical characteristics and the structural design of the actuating mechanism of the vibrator. The "Douti Rotol" Company specializes primarily in the production of high frequency systems which operate in a frequency range of 0-500 Hz with relatively small expulsive forces (< up to 157,500 N) and vibration amplitudes of less than 25 mm. Low frequency systems (0-150 Hz) having large expulsive forces are produced: $\leq 45 \cdot 10^4$ N by the "Feyri" Company and $\leq 67.5 \cdot 10^4$ N of the "MB Electronics" Company, and vibration amplitudes of <150 and <230 mm respectively.

It is expedient to employ hydraulic vibration test systems to test heavily loaded structures, find the resonances of large test objects at large displacement amplitudes for high expulsive forces, and simulate transportation conditions with large amplitudes and low vibration frequencies.

The specific features of hydraulic systems are primarily due to the electrical hydraulic vibrator.

Systems for product testing using the sweep frequency method. A typical block diagram of a testing system using the sweep frequency method is shown in Figure 9, which differs from the circuit shown in Figure 7 in that there is a device in it for automatically running through the frequency range and automatically controlling the level (ARU) [AGC] of the specified vibration parameters. It is an indispensable component of a vibration system designed for tests using the sweep frequency method. All of the electrodynamic, and some of the electrohydraulic systems are put together with such devices.

Vibration test systems which employ the sweep frequency method are closed systems and contain a mater unit 1, which includes an oscillator, a sweep frequency and automatic level control (AGC) unit, a power amplifier 2, vibrator 3, transducer 4, matching amplifier 5 and vibration measurement instrument 6.

A type SUVU-3 control system for vibration installation is employed in a domestic vibration test system as the master unit (Figure 10), where the SUVU-3 contains a sinusoidal voltage generator (1-8), and a vibration transducer 12 with matching maplifier 13, an automatic vibration level control unit (14-20, 2) and a vibration parameter meter 21.

The master oscillator is designed in a beat frequency circuit configuration, and differs from conventional beat frequency generators in that present in the circuit is a selective amplifier 2 with a variable gain, which is the actuating element of the AGC. The generator frequency frequency is changed automatically by sweep unit 8, in which a bidirectional motor is used which is rigidly coupled through a reducer to the shaft of the variable capacitor of the variable frequency oscillator 7. The motor is reversed by means of a microswitch and mechanical stops, placed on the graduated scale of the master oscillator. The rotational speed of the motor is controlled by changing the bias magnetization current of the windings from the direct current source.

The generators of the automatic units of the VEDS type vibration installations are designed around the same circuit, as are the automatic control generators of the 1025 type of the "Bruele and Koer" Company, etc.

The major drawbacks to such systems are the poor stability and precision of the frequency readout on the graduated scale, and the mechanical control of the reverse. These drawbacks have been eliminated in the recent models of the control generators of the "Bruele and Koer" Company: the 1026, 1027 and 1047 types. A crystal and local feedback are used in them to stabilize the frequency, and analog or digital frequency meters are built in to improve the frequency measurement precision. A varicap is employed as the variable capacitor to control the sweep frequency electrically, where the capacitance of the varicap changes in accordance with the change in the DC voltage.

Similar functional components, which provide for electrical sweep frequency control and increase the stability and precision of the frequency readout have been built into the automatic control devices of other companies, for example, in the VCC1 and VCC1-M generators of the "Derritron" Company (England) and the SCO-100 and SCO-200 of the "Ling" Company (England). The SCO-100 and SCO-200 automatic devices, in contrast to other control generators, have output signals with triangular and rectangular waveforms besides the sinusoidal output.

In automatic devices, the frequency scanning rate changes either linearly or logarithmically, and remains constant when running through the frequency range. Vibration tests at a fixed scanning rate have the following drawbacks: the long time to carry out the experiment; the danger of damaging the product at the slow speed; the considerable errors in the determination of the frequency characteristics at a high scanning speed. Systems are known because of this which have a scanning rate dependent on the amplitude-frequency characteristic: it falls off when approaching resonace and increases with increasing distance from resonance.

In the systems described above, piezoelectric acceleration transducers are usually employed as the vibration measurement transducer, which require the introduction of a matching amplifier with a high input impendance into the system.

The most complex assembly which determines the operational quality of the entire system is the automatic level control unit for the vibration parameters (the AGC). It contains two control channels: a channel for adjusting the travel level 14, 16 and 17 (Figure 10) and an acceleration channel, 15 and 16, a compressor, 18-20, and stage 2 with a variable gain. The following requirements are placed on the AGC: it should be stable, have a fast response, have a large dynamic control range and also have minimum nonlinear distortions of the input signal when working in a wide range of frequencies.

The operational principle of the control unit consists in the fact that changes in a specified parameter at the output of the vibration test stand generate proportional changes in the controlling voltage, and consequently, in the gain of the controlled stage and the output signal of the master oscillator. In this case, the specified parameter should be constant. Compressors which respond when a set level is exceeded have become the most widespread in the automatic devices of vibration systems. Depending on the initial working point on the volt-ampere characteristic of the element being controlled, the compressor can perform the functions of an expander, i.e., regulation of the specified level is possible when it falls off.

Any devices, the gain of which changes with the action of the control voltage can serve as the controlled elements. Vacuum tubes, transistors, semiconductor diodes and photoresistors are the devices most frequently used. In some cases, automatic regulators with electromechanical control are used, but because of the large degree of inertia, they have a limited range of applications.

The method of regulation is based on the change in the slope of the input or output conductance with a change in the operating mode of the tube or semiconductor device. In the ideal case, the dynamic range of the change in these parameters should be equal to the dynamic control range. With this method of regulation in a wide range ($\geq$ 40 dB; recent models of the control generators of the "Bruele and Koer" Company have a regulation range of 80 dB), a static control error appears because of the lack of porportionality between the change in the controlled parameter and the controlling voltage; a dynamic error due to the inertia of the smoothing filter of the rectifier of the controlling unit (the compressor); as well as nonlinear distortions due to the nonlinearity of the characteristic of the controlled element and pulsations in the controlling voltage.

It is necessary to utilize the linear section of the change in the controlled parameter of the controlled element to reduce the static error. When the linear portion of the volt-ampere characteristic of a single stage is inadequate, several controlled stages should be employed to cover a wide control range.

The leading foreign firms "Bruele and Koer", "Ling", "Derritron", etc.) use semiconductor components as the controlled element. The static regulation error does not exceed 1.5 - 2.0 dB with a dynamic control range of 70-80 dB. The type 1027 and 1047 devices have a zero static error and control ranges of 90 and 80 dB respectively.

A field effect transisitor is employed as the controlled element in the SCO-100 and SCO-200 automatic devices. This provides for a small time constant in a wide dynamic range. The static error amounts to less than 1.5 dB with a dynamic control range of 60-70 dB.

Domestically produced systems for the automatic control of vibrattion parameters are known, which are designed around transistors, the static control error of which is 1.5-2.0 dB with a dynamic control range of 70 dB.

The dynamic control error depends on the time constant τ of the compressor filter, which determines the control rate (of the compression): the smaller τ is, the smaller the error is, and vice versa. However, in the case of a small τ, nonlinear distortions increase sharply because of pulsations of the

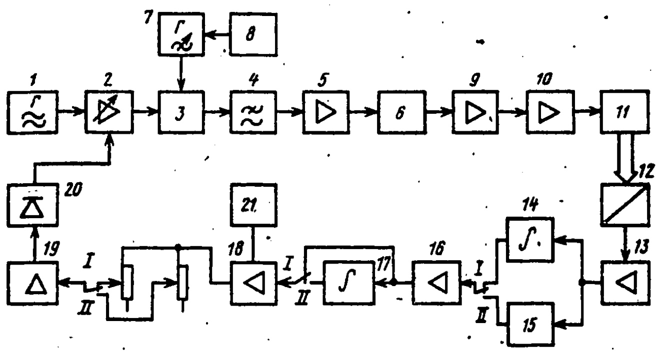


Figure 10. Block diagram of a system for harmonic vibration testing using the sweep frequency method with the SUVU-3 system:

Key: 1. Fixed frequency oscillator;
2. Tuned amplifier with a variable gain;
3. Mixer;
4. Low pass filter;
5. Amplifier;
6. Cathode follower;
7. Variable frequency oscillator;
8. Sweep unit;
9. Peramplifier;
10. Power amplifier;
11. Vibrator;
12. Vibration transducer;
13. Matching amplifier;
14,17. Integrators;
15. Attenuator;
16,18. Amplifiers;
19. Paraphase amplifier;
20. Rectifier;
21. Measurement instrument;
I, II. The switch positions for the travel and acceleration channels respectively.

controlling voltage, especially at low frequencies. In RC filters with a time constant which is variable as a function of frequency are usually employed in domestic and foreign automatic devices. In step with an increase in the frequency, τ decreases, and the ripple factor remains approximately constant while the compression rate G increases.

In domestic, and in many foreign, automated units, the time constant and consequently also the dynamic regulation compression rate is varied in steps manually as well as automatically by means of a mechanical connection (or disconnection) of additional capacitors in parallel with the capacitor having the lowest capacitance C_{min} at f = 3,000 Hz and G = 3,000 dB/sec. The change-over points are:

f, Hz	1,000	300	100	30	10
G, dB/sec	1,000	300	100	30	10

In the latest models of foreign companies, the 1026, 1027 and 1047 (Denmark), and the VCC1M, SCO-100 and SCO-200 (England), the compression rate is varied continuously in accordance with the change in the sweep frequency by means of a tracking filter.

Tuned amplifiers are usually employed as the controlled element for the purpose of reducing the nonlinear distortions which arise during regulation.

One of the special features of automated unit operation is related to the need to maintain the acceleration, velocity or travel (sometimes the sharpness) constant at the monitor point of the vibrator table. It is frequently necessary to maintain a specified travel constant in a specified portion of the working range, while in another part of its range, the velocity or the acceleration is kept constant. In the case of harmonic vibration, these parameters are related by a definite function: the velocity is the first derivative of the travel with respect to time, the acceleration is the second derivative and the sharpness is the third derivative. For this reason, when using an acceleration vibration measurement transducer in a control circuit to derive a signal which is proportional to the velocity, it is necessary to perform one-time integration; for a signal which is proportional to travel, the integration must be performed twice; to obtain a signal proportional to the sharpness, one-time differentiation is performed. Passive RC networks (and recently also active filters) are usually employed as the integrating and differentiating networks.

Shown in Figure 10 are the two most widespread control channels: those based on acceleration and travel. In the latter case, two integrators are used. At low frequencies, the integrating networks introduce an error in the channel transfer function. It is essential for high quality integration that $\omega\tau_{\text{ИНТ}} = [\omega\tau_{int}] >> 1$, where τ_{int} = RC and R >> 1/ωC at the lowest frequency of the working range. Working from the permissible integration error during vibration testing [δ = 1.5 - 3%], one can determine τ_{int} and correspondingly, R and C:

$$\delta = \frac{\omega\tau_{\text{инт}}}{\sqrt{1 + (\omega\tau_{\text{инт}})^2}} 100\%,$$

where ω = 2πf.

When working with integrators at high frequencies, low frequency noise can be considerable. To reduce it, high pass filters are inserted in the integrator circuitry (passive or active filters) with slopes of the frequency response amounting to 12 dB/octave for the case of velocity regulation and 24 dB/octave in the case of travel regulation. In the type 1026 automated units of the "Bruele and Koer" company, there are also so-called dynamic high pass filters, the operation of which is controlled by a digital frequency meter.

For the purpose of eliminating transient processes, the transition from the maintenance of a constant travel to maintaining a constant acceleration, and vice-versa, is usually accomplished at a so-called transition frequency, at which the acceleration, computed on the basis of the travel and the frequency, is equal to the acceleration which should be constant. The changeover is accomplished by means of relays and mechanical stops, positioned on the frequency sweep scale, or by electrical means. A special feature of the 1026 and 1047 automatic devices of the "Bruele and Koer" company is the electrical control of the frequency of the changeover, and the possibility of switching over from one mode to another (for example, from one acceleration level to another) without the presence of nonsteady-state processes. The changeover frequency can take on any value within the range of working frequencies of the generator. There are two identical control channels in the devices which have a common input and which operate from one compressor rectifier. There is the capability of automatic control with respect to acceleration, velocity and travel, both with one channel and when changing over from one channel to another. The operational mode and the level of the corresponding vibration can be specified in each channel independently of the other.

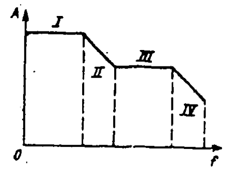


Figure 11. A testing program with automatic changeover from one mode to the other.

Key: A is the amplitude of the vibrations;
f is the frequency;
I. Constant travel;
II. Constant acceleration;
III. Constant travel;
IV. Constant acceleration.

There is a similar multilevel programmer in the SCO-100 and SCO-200 automated units of the "Ling" company (England). Four independent control channels are used in them, by means of which the test program is realized with three changeover frequencies going from travel to acceleration (SCO-100) and from travel to velocity or acceleration (SCO-200). In this case, the test program is characterized by four levels (Figure 11) with automatic changeover from one to the other. External multilevel program units can be connected to any of the channels of the type 1026, 1047, SCO-100 and SCO-200 automated units to perform tests in accordance with the most complex programs, and graphic programming units can also be connected.

Where it is necessary to filter either the measurement or the control signal, the "Bruele and Koer" company recommends the use of the vibration test system, a block diagram of which is shown in Figure 12. The capability of synchronous control of the frequency of the tracking heterodyne filter 2, a type 2021, with a signal from controlling generator 1, or from the tracking frequency multiplier 10, a type 1901, is utilized in this system. Type 1047 or 1026 generators or earlier generator models of the same company (1008, 1019, 1025, 1040, 1041 and 1042) can be used as the control oscillator. The 2021 filter which is tuned from the generator, precisely and instantaneously tracks the frequency of the signal being generated. A type 2021 unit, connected to the control oscillator compressor circuit provides for synchronous filtering of the control signal. The filter bandwidth and the effective averaging time are varied automatically. This makes it possible to control the output voltage of the generator by changing the level of the primary harmonic, which is protected against interference and nonlinear distortion, with the requisite compression rate in the required range of frequencies.

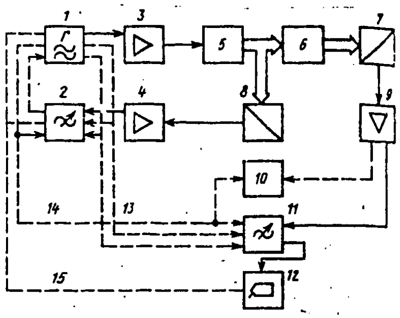


Figure 12. A block diagram of a harmonic vibration test system employing the sweep frequency method with signal filtering in an AGC circuit or with filtering of the signal being measured.

Key: 1. Control oscillator;
2, 11. Heterodyne tracking filters;
3. Power amplifier;
4. Preamplifier;
5. Vibrator;
6. Product being tested;
7, 8. Vibration transducers;
9. Matching amplifier;
10. Multiplier for the tracking frequencies;
12. Level autorecorder;
13. Filter tuning signals;
14. Automatic switching of the bandwidth of the filters;
15. Control of the paper drive for the autorecorder.

In the measurement circuit, when tuned from the generator or from a type 1901 tracked frequency multiplier, the type 2021 tracking filter 11 functions as a tracking filter and serves as a heterodyne frequency analyzer. Since the 1901 instrument provides for electrical control of the paper travel in the type 2307 autorecorder for the level, then the system with the frequency multiplier and the tracking filter can be utilized for automatically recording the frequency characteristics, and also used for harmonic analysis of the vibration signal.

TABLE 2. The Technical Characteristics of Automated Units

	Parameter Параметр	USSR СССР		ENGLAND Англия		
		СУВУ-3 SUVU-3	ВЭДС VEDS	SCO-200	SCO-4A	VCC1-M
(A)	Диапазон частот, Гц	5 – 10 000	5 – 5000	0.1 – 10 000	0 – 10 000	0.1 – 10 000
(B)	Погрешность измерения частоты, Гц	1,0; 2%	0.03f ± 2	0,1%	0,01f ± 0,25	–
(C)	Стабильность частоты, Гц	1,5 за 1 ч работы	±(0,05f + 3) за 1 ч работы	–	–	0,01f
(D)	Скорость развертки частоты	(1 – 60) град/мин deg/min	(7.5 – 75) град/мин deg/min	1 (0.01 – 999) Гц/с; (0,001 – 0,999) 2 окт/с	(0,3 – 335) град/мин deg/min	1 (0,01 – 999) Гц/с; (0,001 – 0,999) 2 окт/с
(E)	Привод развертки	Механический Mechanical		Электронный Electronic		
(F)	Выходное напряжение генератора, В	10*	0,775 ± 10%	6,0*	10	7,5
(G)	Неравномерность АЧХ $U_{вых}$, дБ	1,0		0,5	±0,5; ±1,0	0,25
(H)	КНИ, %	1,0	3,0	0,5	0,5 – 1,0	1,0
(I)	Динамический диапазон регулирования, дБ	40		60		70
(J)	Погрешность регулирования, дБ	1,5	2,0	1,2	2,0	1,5
(K)	Скорость регулирования (сжатия), дБ/с	10; 30; 100; 300; 1000; 3000	10; 30; 100; 300; 1000; 3000	0,1 – 200; 0,3 – 600; 1 – 2000; 3 – 6000	10; 30; 100; 300; 1000; 3000	5 – 5000
(L)	Чувствительность, мВ/g	5,0		1 – 100	–	–
(M)	Входное сопротивление, кОм	$1,5 \cdot 10^6$ (1000 Гц) Hz	$4,0 \cdot 10^4$ (1000 Гц) Hz	$1,0 \cdot 10^6$ (1000 Гц) Hz	> 80	–

Key:
A. Frequency range, Hz;
B. Frequency measurement error, Hz;
C. Frequency stability, Hz: 1.5 after 1 hr of operation [SUVU-3]
D. Sweep frequency rate;
E. Sweep drive;

TABLE 2. [Continued]

"Bruele & Koer" «Брюль и Кьер», Дания Denmark						
1017	1022	1025	1026	1027	1047	
2–2000	20–20 000	5–10 000	1–10 000	2–200 000	5–10 000	(A)
±0,05; 1% ±0,1 Гц Hz	±0,5 Гц; 1% ±1 Гц Hz	0,01f±0,25	0,1; 0,05f	$10^{-5}f$	0,1; 1,0	(B)
–	–	–	0,5 за 8 ч работы 3.	0,07f – на $f_н$; 0,002f – на $f_в$ 4.	0,5 за 8 ч работы 3.	(C)
Привод развертки внешний External Sweep Drive		(0,3–335) град/мин deg/min	(1,0–10^4) 5. Гц/мин; (0,1–100) 6. окт/мин	Привод развертки внешний Ext. Sweep Drive	(0,1–100) Гц/с; (0,1–100) окт/мин	(D)
Механический внешний External mechanical		Механический	Электронный Electronic	7. Электронный, механический	Электронный Electronic	(E)
12,5	12,5	10*	3,0*	10*	10*	(F)
±1,0	±0,5	±0,5; ±1,0	±0,2	±0,1	–	(G)
0,4 (100 Гц) Hz	0,1 (1000 Гц) Hz	0,5–1,0	0,5	–	–	(H)
45	55	60	80	90	80	(I)
2,0	1,5	1,5	1,0	0	0	(J)
3; 10; 30; 100	30; 100; 300; 1000	10; 30; 100; 300; 1000; 3000	1,0; 3,0; 10; 30; 100; 300; 1000	3,0; 10; 30; 100; 300; 1000	10; 30; 100; 300; 1000	(K)
–	–	10				(L)
> 400	25	> 80	> 47	> 25	> 35	(M)

[Key to Table 2, continued]:

F. Generator output voltage, volts;
G. Nonuniformity in the amplitude-frequency response, U_{out}, dB;
H. KNI, % [not further defined];
I. Dynamic control range, dB;

TABLE 2. [Continued]:

Параметр Parameter	USSR СССР		England Англия		
	СУВУ-3	ВЭДС	SCO-200	SCO-4A	VCCI-M
(N) Пределы измерения:	SUVU-3	VEDS			
ускорения, g acceleration, g	1; 3; 10; 30; 100	1; 3; 10; 30; 100	8 (0,1–300) через 10 дБ	1; 10; 100; 1000	(1–300) через 10 дБ in steps of 10 dB
скорости, м/с velocity, m/sec	—	—	(0,01–30) через 10 дБ	—	
перемещения, мм travel, mm.,	—	0,1; 1,0; 10	(0,1–300) через 10 дБ	—	—
(O) Погрешность измерения без учета ИП, %:					
ускорения accel.	4,0	5,0			1,0
скорости velocity	—	—	—	4,0	2,0
перемещения travel	4,0	10,0			
Напряжение сети питания, В Mains supply voltage, volts	220 (f_c = 50 Гц) Hz		115–200–240 (f_c = 50 ÷ 60 Гц) Hz	115–127–150–220–240	
(P) Потребляемая мощность, Вт	—	—	40	80	—
(Q) Габаритные размеры, мм	—	550 × 392 × 365	222 × 432 × 483	—	—
Масса, кг Weight, kg		—	19	25,2	—

* Указано эффективное значение. *The effective value is indicated

[Key to Table 2, continued]:

J. Control error, dB;
K. Control (compression) rate, dB/sec;
L. Sensitivity, mv/g;
M. Input impedance, KOhms;
N. Measurement ranges;
O. Measurement error without taking the IP [not further defined] into account, percent;
P. Power consumption, watts;
Q. Overall dimensions, mm;
1. 0.01-999 Hz/sec;
2. 0.001-0.999 oct/sec;
3. 0.5 after 8 hours of operation;
4. 0.07 f at f_H; 0.002 f at f_B;
5. 1.0-10^4 Hz/min;
6. 0.1-100 oct/min;
7. Electronic, mechanical;
8. 0.1-300 in steps of 10 dB.

[Table 2, continued]:

"Bruele & Koer"		«Брюль и Кьер». Дания Denmark				
1017	1022	1025	1026	1027	1047	
Шкала градуирована в вольтах Scale graduated in volts		1; 10; 100; 1000 $(2{,}5\cdot10^{-3}$– 2,5) через 20 дБ 0,125; 1,25; 12,5	(1 – 1000) через 10 дБ in steps of 10 dB	Шкала градуирована в вольтах и децибелах Scale graduated in volts and decibels	1; 10; 100; 1000 $(2{,}5\cdot10^{-3}$– 2,5) через 20 дБ in 20 dB steps 0,25; 2,5; 25; 250	(N)
2,0	2,0	4,0	0,2 дБ dB	1,0	4,0	(O)
100 – 115 – 127 – 220 – 240 (f_c = 50 ÷ 400 Гц) Hz		100, 115, 127, 150, 220, 240 (f_c = 50 ÷ ÷ 100 Гц)	100 – 115 – 127 – 220 – 240 (f_c = 50 ÷ 400 Гц) Hz			
90	26	80	100	50	80	(P)
480 × 380 × 28[illegible]		520 × 340 × × 510	311 × 500 × × 430	222 × 200 × × 430	177 × 320 × × 430	(Q)
24,5	15	30	30,9	11	10	Weight

The main technical characteristics of automatic devices which are the most widespread in the USSR and which are intended for controlling the mode of vibration tests, are listed in Table 2.

Systems with selectors. When testing by the sweep frequency method, the control of the specified test mode is based on the information received at one (monitor) point where the product is secured to the vibrator table. The amplitudes of the vibrations at other points where the product is fastened can differ substantially from the specified vibration amplitudes. This can lead to a significant reduction in the reliability in the test results. The product in this case can be insufficiently or excessively tested.

For the purpose of improving the reliability of test results in vibration test systems, it is recommended that special devices be used: selectors

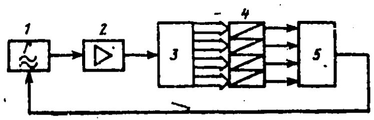


Figure 13. Block diagram of a system for testing by the sweep frequency method using selectors.

Key:
1. Control generator;
2. Power amlifier;
3. Vibrator;
4. Vibration transducer;
5. Selector.

(they are sometimes called averagers). They allow for the control of the test mode based on information obtained as a result of simultaneous measuring the parameters of the test mode at several fastening points of the product. Several transudcers 4 are used in the system, the signals from which are fed through matching amplifiers to selector 5, which generates the control signal (Figure 13).

Many methods exist of generating the control signal by means of selectors. They are dictated by the requirements placed on the vibration tests of a specific product. The following can be cited from among the major methods: the methods of maximum, minimum, and mean levels; vector averaging of the instantaneous peak values of the signals; averaging of the absolute instantaneous peak mean or mean square values of the signals; vector averaging of the instantaneous peak values of the acceleration of a three-component vibration measurement transducer; averaging the signals derived from several three-component transducers. It is necessary for the realization of the maximal level method that the selector automatically and simultaneously compares signals incoming from all of the transducers, and selects the largest of them. This signal is then fed to a control circuit. The maximum level selectors are designed around diodes in an OR gate configuration. Signals from the corresponding transducer are fed to the inputs of the diode rectifiers (usually full wave rectifiers), which are connected in parallel, through matching amplifiers. The highest rectified voltage, which is proportional to maximum amplitude of the vibrations from the amplitudes of the vibrations of all of the monitored points where the product is fastened, cuts off the remaining diodes. This voltage is filtered, converted to a variable frequency voltage and fed to the control circuit described above. The conversion of the DC voltage to an alternating one is necessary for matching to the control circuit. This is usually performed by a simple chopper at a frequency f = 60 Hz. This frequency is sufficient to provide for precise control. However, it permits the realization of only acceleration control. If it is additionally necessary to provide for travel and velocity control, then the chopper should be replaced by a multiplier, which multiplies the rectifier voltage times the signal from a constant frequency sinusoidal voltage source.

An advantage of a maximum level selector is the practical total elimination of the possibility of excess testing of the product, while a drawback is the possibility of substantial undertesting. Maximal level control is effective at frequencies below 200 Hz, where the large displacements can lead to structural damage. At frequencies above 200 Hz, especially in the case of testing large objects, this method leads to test conditions which do not correspond to operational conditions.

Domestic vibration test systems are well known which have maximum level selectors, for example, the 10 channel PV-10K type and the 20 channel PKMU type.

The minimum level method consists in the selectors singling out the lowest amplitude of the vibrations from the amplitudes of the vibrations of all of the fastening points being monitored, and controlling this quantity when the test mode changes. At other points, the amplitude of the vibrations can be substantially greater than the requisite level, something which leads to a considerable overtesting, because of which, this method has not found wide use in vibration testing practice.

The mean level method is the most optimal procedure, in which the danger of overloading is eliminated, and the possibility of undertesting a product is reduced to a minimum. In the process of vibration testing control using a mean level selector, the mean acceleration is kept constant for all of the points being monitored.

With the vector averaging of the instantaneous peak values of the signals derived from several transducers, the sum of the vectors can be equal to zero. In this case, when maintaining a specified mode, the product is subjected to the action of the maximum loads which the given vibration system can develop. As a result of this, the product can fail, and for this reason, the method of vector averaging has not found wide application.

The major drawback to the methods of averaging with respect to the absolute value of the instantaneous peak values of signals, or with respect to the mean or mean square value, is related to the fact with a reduction in the acceleration at some of the control points, in other points, the acceleration, and consequently also the input level of the corresponding selector channels is increased proportionately. At these points, the product is overtested, while the corresponding channels of the selector are overloaded. The worst case condition is when the acceleration drops to zero at all of the points being monitored with the exception of one. The acceleration at the acting point and the input signal of the corresponding channel are increased by n times (n is the number of points being monitored). For this reason, each channel should have an n-tuple reserve with respect to a specified mean level. But even in this case, the method under consideration has an advantage over the method of averaging the instantaneous peak values as being more reliable and less dangerous. An additional drawback is the difficulty of the circuit design realization of the rectifiers for the mean square values, which have the requisite linear range.

The method of averaging the mean values of signals has become the most widespread of all of the averaging methods enumerated here. It consists in the determination of the mean value for each signal, summing them and the division of the resulting sum by the number of points being monitored. The mean value is determined by means of a mean value rectifier. The time constant of the rectifier filter, usually designed as an RC network, is 0.1 to 0.5 seconds.

It provides for reliable control in a frequency range of 20-2,000 Hz (the working range of all the selectors) at compression rates of 80-100 dB/sec. Higher compression rates lead to control instability. The time constant can be minimized by means of optimizing the capacitance of the filter capacitor with respect to the frequency passbands. Adding and dividing by a constant number n is usually accomplished by an operational amplifier. The DC voltage at the output of the operational amplifier is converted to an AC voltage with a fixed or variable frequency, and is fed to a control circuit. In this method of averaging, it is not necessary to use additional filters, something which is an advantage of it. For example, the method considered here has been realized in the type 4410 selector of the Danish company "Bruele and Koer". These selectors have a small number of monitored channels (4-6). Increasing the number of channels is limited by the nonlinearity of the rectifier characteristic, which is manifest at low input signal levels.

Selectors are known which realize combination methods of generating the control signal, for example, a four channel selector developed in the US (maximum and mean level methods), as well as the type 4410 four channel selector and type 5686 six channel selector of the "Bruele and Koer" Company (maximum, minimum and mean level methods).

Systems with testing mode control and mechanical impedance compensation. In vibration test systems, designed for testing products using the sweep frequency method, the influence of mechanical impedances of the product being tested and the moving portion of the vibrator is not taken into account.

The simplest and most effective method of reducing the mutual influence of mechanical impedances is the compensation method, based on the control of the specified testing mode by a signal proportional to the product of force times acceleration. It differs from other compensation methods for mechanical impedances in that in this case, one does not have to know the dynamic characteristics of the control object and the phase relationships between the force and the acceleration. To realize this method, it is necessary to additionally incorporate a force transducer 5, two logarithmic transducers 8 and 9, and an operational amplifier 10, which accomplishes the summing of the logarithms of force and acceleration (Figure 14) in the complement of a conventional vibration test system designed for sweep frequency testing.

In this system, any of the described domestic and foreign generators can be used as the controlling generator. When a type 1047 generator is used, for example, system capabilities can be expanded through the introduction of tracking filters, autorecorders, multilevel programming devices, etc. into it. For example, a type 8200 force transducer of the "Bruele and Koer" Company or a type 2103-500 force transducer of the "Endevko" Company (US), etc., can be used as the force transducer.

Polyharmonic vibration testing system. The systems primarily used for the vibration testing of products for polyharmonic vibration are those with electrodynamic excitation. Several standard master oscillators are used to obtain a complex polyharmonic signal. The appropriate frequencies from the oscillators are fed directly to the input of a conventional vibration test stand amplifier.

The "Bruele and Koer" Company recommends the use of several control generators in such systems, for example, of the 1047 type, as well as several heterodyne tracking filters of the 2021 type. The vibration test system is somewhat simplifed when type 1026 control generators are used, in which the tracking filters are built in. In this case, two or more generators can be used with one vibrator, each of which provides for frequency sweep in a different range, independently of one another. The signals from the outputs of the control oscillators are added and act on the vibrator through a power amplifier. Automatic control of the testing mode is accomplished separately for each generator synchronously with the specified frequencies by means of the tracking filters. The block diagram of such a system is shown in Figure 15. Type 1026 control generators are used in it.

The composite signal in such systems proves to be nonsteady-state in terms of its wave form because of the continuous change in the phase shift between the components. This drawback can be eliminated if the master oscillator used in the vibration system, intended for sinusoidal vibration testing, is replaced by a standard complex waveform generator, for example, of the G6-1 type (USSR), which makes it possible to obtain the sum of the first through the sixth harmonics with controllable amplitudes and phases for each harmonic. When a complex waveform generator is present in the vibration system, the tests can be conducted using a strictly sinusoidal signal at the output of the vibrator, since it becomes possible to compensate for nonlinear distortions.

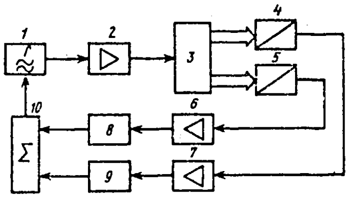


Figure 14. Block diagram of a system for sweep frequency testing with compensation of the mechanical impedance.

Key: 1. Control oscillator; 2. Power amplifier; 3. Vibrator with the product; 4. Acceleration transducer; 5. Force transducer; 6,7. Matching amplifiers; 8,9. Logarithmic transducer; 10. Adder (operational amplifier).

A block diagram of such a system is shown in Figure 16.

The sinusoidal voltage from the master oscillator 1 is fed to the harmonic driver (frequency multiplier) 2 and the first harmonic amplifier with the level controller 3. The harmonic components are singled out and amplified by means of active filters 4, which have level controllers, and fed through graduated phase shifters 5 to adder 6, to which the first harmonic signal is applied. The composite signal is fed through preamplifier 7 and power

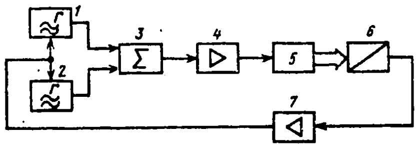


Figure 15. Block diagram of a system for polyharmonic vibration testing using the sweep frequency method:

Key:
1,2. Control oscillators;
3. Adder;
4. Power amplifier;
5. Vibrator;
6. Vibration transducer;
7. Matching amplifier.

amplifier 8 to vibrator 9. The mechanical oscillations of the vibrator are converted to electrical oscillations by means of transducer 10 and fed through matching amplifier 11 and analyzer 12 (a set of tunable narrowband filters) to oscilloscope 13 and measurement instrument 14. A distinctive feature of a such a system is the capability of adjusting the phase shift between the harmonic during the setting of the specified mode as wellin the testing process.

A system has been developed in the USSR for controlling vibration tests in the case of polyharmonic power excitation, which is a multichannel closed system. Each channel in this system stabilizes the harmonic component of the acceleration at a frequency F_i. The control object is an electrodynamic vibrator with a preamplifier and a power amplifier. Fed to the input of the preamplifier from the output of the multichannel master oscillator is a complex harmonic signal.

The output quantity of the system is the acceleration at the vibrator test table, measured by means of a vibration measurement transducer. The signal from the latter is fed through a matching amplifier to a block of analyzers, which takes the form of a parallel harmonic analyzer, which is based on synchronous detection and which isolates the individual harmonic component at the frequencies F_i. The signals of the individual channels of the analyzers are the feedback of the control system; they are compared with the signals of the master oscillator block. Difference signals are fed to the block of controllers, which control the output voltages of each channel of the master oscillator block. We shall consider the operational principle of the master oscillator block and the analyzer. The master oscillator block (Figure 17) contains a common section, which provides for the operation of all of the oscillator channels, and switchers and frequency drivers for each channel. There is the capability of selecting any of 100 discrete frequencies in each channel.

The following are included in the common section of the generator circuit: heterodyne oscillators 1, 2 and 3; the 20 mixers for the units digit, 4; the 20 bandpass filters for the units digit 5; the 17 mixers for the tens digit, 6; the 17 bandpass filters for the tens digit, 7; adder 12; common mixer 13 and low pass filter 14.

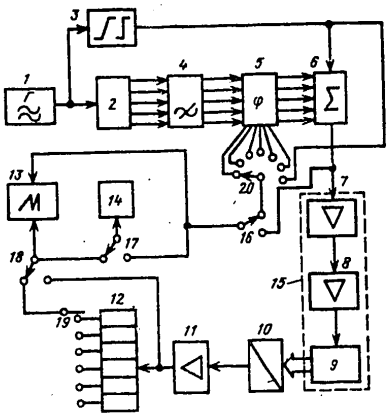


Figure 16. Block diagram of a system for polyharmonic vibration testing.

Key: 1. Master oscillator;
2. Frequency multiplier;
3. Level controller; 4. Filter;
5. Phase shifter; 6. Adder;
7. Preamplifier; 8. Power amplifier; 9. Vibrator;
10. Vibration transducer;
11. Matching amplifier;
12. Analyzer; 13. Oscilloscope;
14. Measurement instrument;
15. Vibration test stand;
16-20. Switches.

Two switches 8_1 and 8_2, mixer 9, bandpass filter 10 and controlled gain amplifier 11 are used to generate the requisite harmonic component in each channel.

The crystal heterodyne oscillator is intended for the frequency stabilization of the reference voltages, necessary for the operation of the analyzers. The difference in the tuning of heterodyne oscillators 1 and 2 determines the discrete step of the generated frequency. Let the difference in the frequencies of the heterodyne oscillators be $F = f_2 - f_1$. Signals from the first heterodyne and the crystal heterodyne oscillator are fed to the first mixer. The bandpass filter which is inserted after the first mixer singles out the total frequency $(f_{crys} + f_1)$. The signal at this frequency is fed to the units digit mixer and the tens digit mixer. As a result of the successive transformation in the units digit, signals are generated at frequencies of $(f_{crys} - nF + f_1)$ and $[f_{crys} - (n+1)F]$, and in the tens digit, $(f_1 + f_{crys} + 10nF)$ and $[f_1 + (n+1)10F]$, where n is integers from 0 to 9.

Thus, there are ten units digit frequencies and 10 tens digit frequencies in the common section of the generator. By means of the switchers in each channel, any frequency from the units digit can be mixed with any frequency from the tens digit. Following mixing, each bandpass filter isolates the difference frequency signal:

$$(f_1 - n_1F + f_{\text{кв}}) - (f_1 + 10n_2F) = f_{\text{кв}} - (n_1 + 10n_2)F,$$

where n_1 and n_2 are integers from 0 to 9; 1 and 2 are subscripts corresponding to the position of the switches 8_1 and 8_2.

Consequently, in each channel when switching with the switches there is the possibility of selecting any of 100 discrete frequencies with a discrete interval of F.

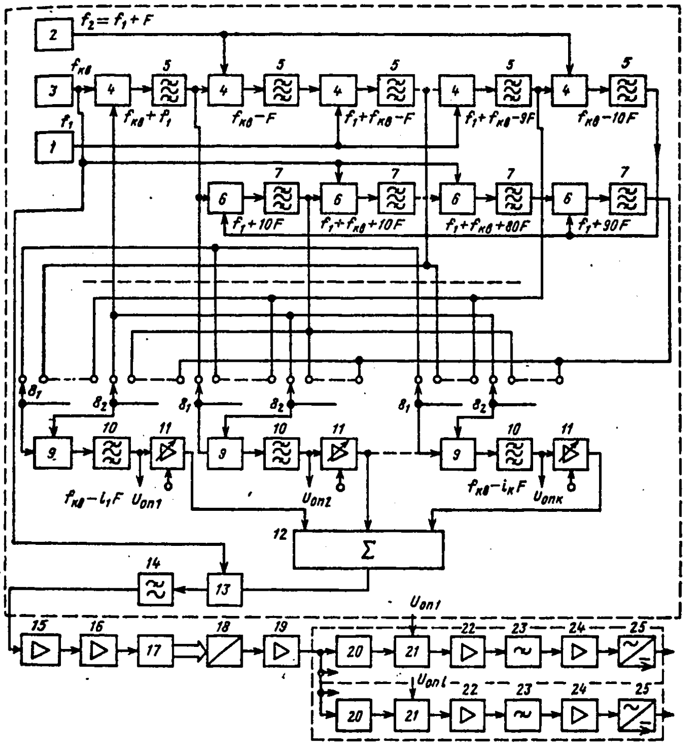


Figure 17. Block diagram of a closed multichannel system for poly-harmonic vibration testing.

Key: 1,2. Heterodyne oscillators; 3. Crystal heterodyne oscillator; 4. Units digit mixers; 5. Bandpass filters; 6. Tens digit mixers; 7. Bandpass filters for the tens digit; 8. Switches; 9. Mixers; 10. Bandpass filters; 11. Adjustable gain amplifiers; 12. Adder; 13. Common mixer; 14. Low pass filter; 15. Preamplifier; 16. Power amplifier; 17. Vibrator; 18. Vibration transducer; 19. Matching amplifier; 20. Emitter followers; 21. Synchronous detectors; 22,24. Amplifiers; 23. Selective crystal filters; 25. Rectifiers with filter.

Following the bandpass filters 10, the signals of each channel are fed through the variable gain amplifier 11 to the adder 12. To shift the complex signal spectrum into the low frequency range, the composite signal and the crystal heterodyne oscillator signal are mixed in the common mixer 13. Low pass filter 14 passes the difference frequency signal. Thus, we obtain an output voltage which contains the requisite harmonic component, the number of which is determined by the number of generator channels and the requisite nature of the force excitation. This signal is fed through preamplifier 15 and power amplifier 16 to vibrator 17. The reference signals, $U_{on\ i}$, for the block of analyzers are picked off from the bandpass filters 10 from each channel.

The i-th channel analyzer consists of the following series connected sections: matching amplifier 19; emitter follower 20; synchronous detector 21, which operates in the frequency mixing mode; voltage amplifier 22; selective crystal filter 23; amplifier 24 and the rectifier with a filter 25, the signal from which is fed to the variable gain amplifier 11.

A distinctive feature of this system is the capability of obtaining a large number of discrete harmonics with a variable gain for each one, something which permits the simulation of a random process with a specified spectral density in the requisite frequency range. In this case, the test conditions approach operational conditions.

A feature of the circuit design of the system is the multichannel nature and closed aspect of the system, which permit the stabilization of the level of each harmonic. The precision in the operation of the system in the case of high open loop gain is basically determined by the errors in the feedback circuit.

Systems for Random Vibration Testing

Systems for wide band random vibration testing. The transfer function of the vibrator--product mechanical system changes with a change in the vibration frequency and the product properties. The results of full-scale product tests are shown in Figure 18. It can be seen that are three sharp resonances of the structure of the product being tested at frequencies of 740, 1,200 and 1,600 Hz on the curve (Figure 18a) for the ratio of the acceleration to the input voltage, μ, as a function of the frequency, besides the resonance at the center frequency of about 120 Hz and the high frequency resonance (≃ 1,200 Hz), due to the properties of the vibrator. Shown in Figure 18b is a curve in which the vibrator resonances have been corrected, in which case, the natural resonances of the structure of the product being tested have not been eliminated. Shown in Figure 18c is a curve which illustrates the total equilization of the resonances of the vibrator and the structure being tested.

To compensate for the nonuniformity of the amplitude-frequency response of the vibrator, equalizing devices are needed, the frequency characteristic of which is the inverse of the frequency characteristic of the vibrator with the product mounted on its table. To compensate for the resonances of the vibrator--product system, similar correcting devices are needed having a frequency characteristic which is the inverse of the frequency characteristic of the vibrator--product system. For this reason, in vibration test systems, for the purpose of compensating for the resonances (peaks) and antiresonances (valleys), special devices, equalizers, are introduced into addition to the devices which specify, reproduce and analyze the test mode. Two systems for generating a spectrum of wideband reandom vibrations are employed as such equalizers: systems with selective tunable filters, which can be tuned to the peaks and valleys in the frequency response of the vibrator--product mechanical system; and systems with comb filters, which can have either manual or automatic control of the amplitude-frequency response of the vibrator--product system.

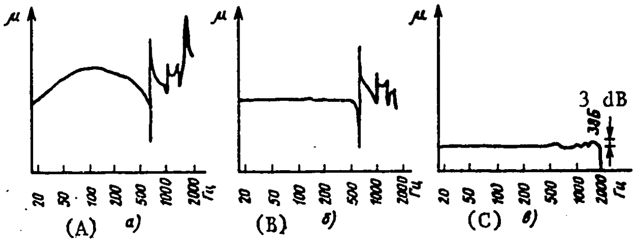


Figure 18. The amplitude-frequency response curves of the vibrator--product system:

Key:
a. Without compensation for the resonances;
b. With compensation for the vibrator resonances;
c. With compensation for the vibrator and product resonances.

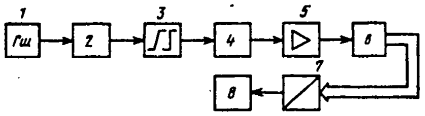


Figure 19. Block diagram of a system for wide band random vibration testing with tunable filters.

Key: 1. Noise generator; 2. Programmer for the acceleration spectral density; 3. Equalizer; 4. Excitation level regulator; 5. Power amplifier; 6. Vibrator with the product; 7. Vibration transducer; 8. Spectrum analyzer.

Amplitude-frequency response equalizers with tunable filters. Shown in Figure 19 is a block diagram of a system with tunable filters. Each of the compensators of the equalizer 3 in such systems take the form of a device which contain tunable filters with a variable Q and analog computer components, which realize inverse mathematical functions. The filters make it possible to produce peaks and valleys in the frequency response. By tuning them to the peaks and valleys in the frequency response of the mechanical system, recorded manually or by means of a recorder, and introducing a definite attenuation in each filter, one can achieve complete equalization of the frequency response of the vibrator--product system. This equalization procedure is accomplished prior to testing, for which a low level sinusoidal signal (≈ 0.1 of the specified level) is fed to the input of the equalizer, so as not damage the product. A signal of the specified spectral density in the requisite frequency range is fed to the input of the equalizer from noise generator 1 through the programmer for the acceleration spectral density 2, or it is supplied from the output of a tape recorder on which the actual vibration process is recorded.

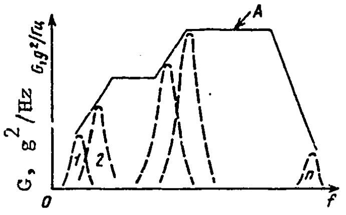


Figure 20. Scheme for the generation of the acceleration spectral density by means of comb filters.

Key: 1,2, ... n. The amplitude-frequency response of the filters;

Curve A is the level of the spectral density.

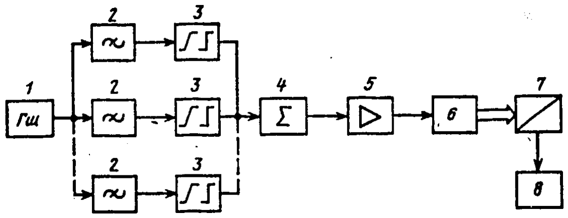


Figure 21. Block diagram of a system for wideband random vibration testing with comb filters (manual control).

Key: 1. Noise generator; 2. Filters; 3. Level controller; 4. Adder; 5. Power amplifier; 6. Vibrator; 7. Vibration transducer; 8. Parallel analyzer.

Such a method of equalizing the frequency response is effective, and using it, one can obtain better equalization (with an accuracy of ± 3 dB). However, it has not found widespread application because of substantial drawbacks. These included the necessity of recording the amplitude-frequency response of the system prior to making the tests; the complexity of the alignment, especially in the presence of a considerable number of resonances; the impossibility of generating the spectrum of a random vibration process which differs from a flat one; and the necessity of retuning the equalizer when the resonances of the object change during the resting process.

Manual amplitude-frequency response equalizers with comb filters. It is convenient to equalize the frequency characteristic of the mechanical system of the vibrator--product and generate the specified spectral acceleration density by means of breaking the spectrum of the input signal down into a large number of narrow frequency bands by means of a set of narrow band filters, connected in parallel, or so-called comb filters.

The possibility of designing a system with comb filters is due to the fact that when generating the spectral density, a change in the time-wise form of the random process may not be taken into account. For this reason, a certain definite mean level of the spectral density in a narrow frequency band can be specified in each individual protion of the spectrum. However, for purpose of obtaining a sufficiently precise reproduction of the specified spectral density, it is essential to strictly observe the uniformity of the input noise signal, as well as the nattow band response and rectilinear nature of the amplitude-frequency response of the filters.

Thus, a narrow band equalizer with comb filters breaks the spectrum of the random signal coming from the noise generator down into n adjacent bands with a variable attenuation in each band.

A spectral density curve (curve A) for the acceleration at a specified point on a vibration test stand or a product, obtained by means of comb filters is shown in Figure 20.

The value of the acceleration in a narrow band of frequencies Δf is obtained by integrating the acceleration spectral density in this passband and is monitored by means of an analyzer having a filter for each band similar to the filter generating the spectrum; as well as a square-law detector, an integrator (averaging device) and a recorder.

A block diagram of a vibration test system with comb filters is shown in Figure 21.

Noise generator 1 generates a signal which has a uniform spectral density in the requisite frequency range. This signal provides excitation in all of the frequency band simultaneously. Using s spectrum analyzer, the nonuniformity of the amplitude-frequency response of the vibrator--product system is determined. By adjusting the output levels of the signal from the output of the filters 2 by means of level controls 3 manually, the amplitude-frequency response is equalized and the specified spectrum is generated, which is fed to vibrator 6 from adder 4 through power amplifier 5. To provide for good equalization and precise generation of the specified spectral density of the random process, each filter should have as narrow a passband as possible (it is limited by the averaging time of the spectral density measurement channel and the complexity of the filter design) and as great a control depth as possible with sufficient rectilinearity of the amplitude-frequency response. The "MB Electronics" Company (US) recommends the use of 80 filters with independent control of the attenuation of each filter in the amount of 45 dB to cover a frequency range of from 0 to 2,000 Hz. In this case, the nonuniformity in the overall-frequency response of the block of generating and analyzing filters does not exceed 3-3.5 dB. To cover a range of from 10 to 2,000 Hz, the "Derrotron" Company (England) recommends that there be 48 filters in such a test system and the "Pay-Ling" Company (England) offers 27 third-octave filters to cover the range from 20 to 2,000 Hz.

The spectral density level of the random process reproduce by the vibrator is monitored by means of a measurement instrument and an analyzer, which allows for the measurement of the acceleration spectral density throughout the entire specified frequency range or at any of the narrow frequency bands, isolated by means of the analyzing filters, identical to the filters of the generation unit (the equalizer). As a rule, there is a cathode ray tube display with long persistence at the output of the analyzer. It makes it possible to observe the picture of the vibration spectrum when aligning the system, as well as the during the testing process. By comparing the resulting spectral density with the specified one, the precision in the execution of the program is assessed.

An actual vibration recorded on magnetic tape can be reproduced by means of such systems. In this case, a tape recorder is used instead of the noise generator, and a sinusiodal voltage generator is used to equalize the frequency response of the vibrator.

These systems have found limited applications because of the existing deficiencies. Manual equalization of the frequency response and the generation of the specified spectrum in the case of a large number of channels takes up a great deal of time and can run up to several hours, in which case, the service life of the product being tested is exhausted. Instability in the operation of circuit components, especially the noise generator, has an influence on the results, since the control system is an open loop type.

The technical characteristics of manual control systems for wideband vibration are shown in Table 3.

The principle of spectrum splitting of the input signal into a series of narrow frequency bands by means of comb filters, just as in the case of manual control, is utilized in *vibration test systems with automatic control of wideband random vibration*. However, automatic level control devices (AGC) in each frequency band are included in the complement of systems with automatic control.

The block diagram of the SUVU-ShSV-2 80-channel automatic control system for wideband random vibration which was developed in the USSR is shown in Figure 22.

A noise signal with a uniform spectral density in a specified frequency range (from 5 to 5,000 Hz) is fed from noise generator 1 to the block of driving filters 2 and broken down into 80 adjacent bands. Noise generator 1 has two channels with independent noise sources, and in this case, the even filters of the equalizer are connected to one channel while the odd filters are connected to the other channel of the noise generator to avoid cross-correlation of the output signals of two adjacent filters [it is assumed that the amplitude-frequency response of the i-th filter is overlapped only by the amplitude-frequency response of the (i±1) filters]. There are two variable gain amplifiers 3 at the output of driving filters 2. The signal from the outputs of the amplifiers is fed to adder 4 and through low pass filter 5, level attenuators 7 and preamplifier 10 to power amplifier 11, which drives the electrodynamic vibrator 15. The spectrum of random vibration which is reproduced by the vibrator is monitored by means of pizzoelectric measurement transducer 12, mounted on the vibration test stand or on the product.

The signal from the output of the measurement transducer is fred through matching amplifier 13 to meter 14 for the mean square values of the acceleration in the working frequency band and to attenuator 8, which is mechanically coupled to attenuator 7, inserted in the circuit for generating the specified spectral density. The presence of such coupling between the attenuators is dictated by the necessity of maintaining the overall gain of the closed loop constant when the attenuation level changes. The signal is fed from the level attenuator through amplifier 16 to analyzer filters 17, which are identical to the equalizer filters. The signals are fed from the output of each analyzer filter through multiplier 18 to the feedback amplifiers 19, where they are detected and fed to monitor unit 20 for the spectral density of each channel. The AC signal goes from amplifiers 19 through potentiometers 21 to the AGC unit 22 of each channel, which controls the gain of the device. The specified acceleration spectral density level is programmed in the requisite frequency range by means of multipliers and potentiometers.

The measurement instrument makes it possible for the operator to be sure that the AGC unit is operating in the active range. All of the foriegn series produced vibration test systems with automatic wideband vibration control are designed on this principle (Table 4).

The systems differ from each other basically in the frequency coverage, the number of channels, the bandwidth of the filters and the structural design.

The primary frequency range is the band of frequencies from 10 (in some systems from 20 Hz) to 2,000 Hz. As a rule, this range is covered by 40 to 80 channels, each of which includes one generating and one analyzing narrow band filter. With an increase in the number of channels, the bandwidth of the filters decreases correspondingly when the same frequency range is covered. As a rule, the bandwidth of a filter does not exceed 75 Hz (taking into account the fact that the least width of the resonance curve of the samples being tested reaches 100 Hz at average frequencies). In some systems, filters with an identical absolute bandwidth are taken as the basis, where the bandwidth is 50 Hz for a 40 channel system, for example,

TABLE 3

The Technical Characteristics of Manual Control Systems for Wideband Vibration

Type, Тип, фирма Company	(A) Диапазон частот, Гц	(B) Число каналов	Ширина полосы частот фильтров, Гц (C)	Фильтры Filters	(D) Динамический диапазон, дБ	(E) Средства анализа и измерения
SPV-2 СПВ-2 (СССР) (USSR)	20 – 2000 20 – 5000	30 36	$\frac{1}{4,5}$ окт oct.	Активные *RC* Active RC	30	$^1/_{4,5}$-октавные фильтры; осциллограф типа И-Ч (1)
"Pay-Ling" «Пай-Линг» (Англия) (England)	20 – 10 000	27	$\frac{1}{3}$ окт oct.	Пассивные *LC* Passive LC	45	$^1/_3$-октавные фильтры; осциллограф (2)
ME/MA «Линг» (Англия) ME/MA "Ling" (England)	10 – 2000	26; 39 52	10, 11, 12, 13, 14, 30, 50, 100 10, 11, 12, 13, 14, 15, 16, 17, 18, 25, 30, 50	–	60	Фильтры, аналогичные фильтрам выравнивателя; осциллограф; вольтметр (3)
«Дерритрон» (Англия) "Derritron" (England)		48	12,5; 25; 50	Пассивные магнитострикционные (100 кГц) (4)	50	Анализатор; двухкоординатный самописец (5)
(6) Т-495, «МБ Электроникс» (США)				Кварцевые (100 кГц) Crystal	60	
(7) «МБ Электроникс» (США)	0 – 2000 2000 – 4000 4000 – 6000 ...	80	25	Магнитострикционные (100, 98, 96 кГц) (8)		Анализатор: осциллограф Analyzer; Oscilloscope
7208, «VDY» (Япония) (Japan)	10 – 2000 2000 – 4000 4000 – 6000		12.5; 25; 50	Магнитострикционные (100 кГц) Magneto-strictive (100 KHz)	50	
	10 – 3000 3000 – 6000 6000 – 9000		25; 50			

Key: A. Range of frequencies, Hz;
B. Number of channels;
C. Bandwidth of the filters, Hz;
D. Dynamic range, dB;
E. Analysis and measurement tools;
1. 1/4.5-octave filters, a type I-Ch oscilloscope;

[Key to Table 3, continued]:

2. 1/3-octave filters; oscilloscope;
3. Filters similar to the equalizer filters; oscilloscope; voltmeter;
4. Passive magnitostrictive (100 KHz);
5. Analyzer; two-coordinate autorecorder;
6. T/495, "MB Electronics" (US);
7. "MB Electronics" (US);
8. Magnitostrictive (100, 98, 96 KHz).

Note: The error in the spectral density generation is less than 3.0 dB.

The ARN-1 (England), 25 Hz for an 80 channel system, for example, the VKV-4500 (USSR). In other systems, the bandwidth varies from 7.5 to 50 Hz, for example, SUVU-ShSV-2 (USSR), in which case four passbands are employed: 7.5 Hz (1 unit); 12.5 Hz (2 units); 25 Hz (62 units) and 50 Hz (6 units). There are also 30, 60 and 120-channel systems used in the same frequency range; for example, the 3378, 3379 and 3380 systems of the "Bruele and Koer" Company (Denmark).

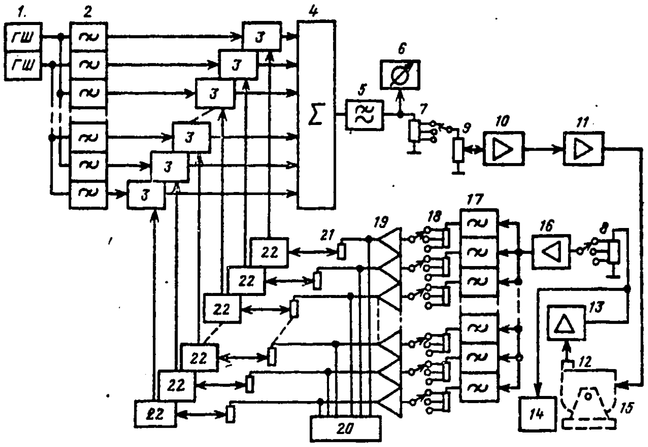


Figure 22. Block diagram of a system for wideband random vibration testing (automatic control):

Key: 1. Noise generator; 2. Equalizer filters; 3. Device with a variable gain; 4. Adder; 5. Low pass filter; 6. Measurement instrument; 7,8. Attenuators; 9. Output level control; 10,16. Amplifiers; 11. Power amplifier; 12. Vibration transducer; 13. Preamplifier; 14. Acceleration vibration meter; 15. Vibrator; 17. Analyzer filters; 18. Level multiplier; 19. Feedback amplifier; 20. Spectral density monitor; 21. Programming potentiometer; 22. Automatic gain control.

TABLE 4

The Technical Characteristics of Automated Control Systems for Wideband Vibration

Тип Type	(A) Диапазон частот, Гц	(B) Число каналов	(C) Ширина полосы частот фильтров, Гц	(D) Динамический диапазон регулирования, дБ	(E) Погрешность измерения, дБ	(F) Максимальное выходное напряжение, В	Фильтры Filters
			USSR СССР				
SUVU-ShSV-2 СУВУ-ШСВ-2	5–2000	80	7,5(1); 12,5(11); 25(62); 50(6)	40	±0,5	10	Passive LC Пассивные LC
ВКВ-4500 VKV-4500	10–2000; 2000–4000; 4000–6000; 6000–8000; 8000–10 000		25	50	±1,0	–	Кварцевые (99 кГц) Crystal (99 KHz)
"Bruele & Koer", Denmark «Брюль и Къер», Дания							
3378	1–584	60	1–2,8(10); 5,2–15,8 (50)	60	±3	2,0; 10	Активные RC Active RC
3379	20–2000		10–50(60)				
3380		120	5–25(120)				
По заказу On order	20–2000 20–1000	30 150	20–100(30) 2,5–10(150)				
	2000–10 000	100 50	30–175(100) 60–350(60)				
"Ling", England «Линг», Англия							
ASDE-40	10–2000	45	10, 11, 12, 13, 14, 30 по одной штуке 50(39)	50	±0,5	2,0	Пассивные LC Passive LC
ASDE-80		85	10, 11, 12, 13, 14(2); 15, 16, 17, 18, 25(75)				
HFSD-40	2000–4000	40	50			2,8	
HFSD-80		80	25				

Key:
A. Frequency range, Hz;
B. Number of channels;
C. Bandwidth of the filters, Hz;
D. Dynamic control range, dB;
E. Measurement error, dB;
F. Maximum output voltage, volts;
1. Three sets of the ARN-40, or ARN-80; 37.75 (or 80).

Notes:
1. The nonuniformity in the spectral density generation is no more than ± 1.5 dB.
2. The control error in domestic AGC units is no more than ± 15. dB, and no more than ± 1.0 dB for the remaining systems.

TABLE 4, continued:

Тип Type	Диапазон частот, Гц (A)	(B) Число каналов	Ширина полосы частот фильтров, Гц (C)	Динамический диапазон регулирования, дБ (D)	Погрешность измерения, дБ (E)	Максимальное выходное напряжение, В (F)	Фильтры Filters
	"Derritron", England		«Дерритрон», Англия				
ARN-40	10 – 2000	40	2,22 – 67,35(18); 74,07(22)	50	±0.5	–	Magneto-strictive (100 KHz) Магнитострикционные (100 кГц)
ARN-80		80	1,1 – 35(36); 37,1(44)				
ARN-80	10 – 5000	80	2,22 – 67,35(18) 74,07(22); 75(40)				
ARN-120 ARN-160	10 – 1000 10 – 5000	120 160	Три комплекта ARN-40 1. ARN-80; 37,75(80)				
ARN-1(2)	10 – 2000 20 – 4000; 4000 – 6000; 6000 – 8000; 8000 – 10 000	40	25(1); 50(39)				
	"SARA", France		«САРА», Франция				Passive, LC
SARA	10 – 20 000	81	$\Delta f = 4{,}6 f^{0{,}20}$	50	–	–	Пассивные *LC*
	"Chinken", Japan		«Чинкен», Япония				Crystal
G02-028	10 – 2000	80	–	60	±0.5	–	Кварцевые

The frequency range can be extended up to 5000-10,000 Hz by adding channels to the basic system, as a rule, with an identical absolute passband of the filters (the ARN, VKV-4500, SUVU-ShSV-3, etc.).

The basic problem which is faced in the design of wideband random vibration control devices consists in generating at the input of the object being controlled (the vibrator with the product) that spectrum which differs from the specified one at the output of the object by no more than the permissible overall error:

$$\varepsilon_{\Sigma} \geqslant \frac{|G_y(f) - G_x(f)|}{G_x(f)},$$

where $G_y(f)$ is the spectral density at the output of the control object; $G_x(f)$ is the specified spectral density.

The overall permissible error ε_{Σ} includes the approximation and analysis errors, as well as the statistical and equipment errors.

The approximation error, ε_{appr} is due to the manner of generating the spectral density functions by means of noise generator and a set of bandpass filters. It characterizes the absolute value of the deviation of the spectral density function at the output of the generation unit from the derived specified function $G_{x1}(f)$ (the spectral desnity at the input to the control object) and is a decaying function of the number of generating filters.

$$G_{x1}(f) = \frac{G_x(f)}{|\Phi_0(jf)|^2},$$

where $\Phi_0(jf)$ is the transfer function of the control object.

The approximation error for the i-th channel is expressed by the relationship:

$$\varepsilon_{\text{аппр}} = \frac{\Delta f^2}{24}\ddot{G}_x(f),$$

where Δf is the passband of the narrow band filter; $\ddot{G}_x(f)$ is the second derivative of the spectral density (a measure of spectral smoothness).

The approximation error is a function of the passband and the shape of the spectral density. The more uniform the spectrum, the smaller the error; with a completely uniform spectrum, it is equal to zero. The digitization step of the spectrum and the form of the amplitude-frequency response of the narrow band filter have a substantial influence on the approximation error. In the case of an ideal filter with a rectangular amplitude-frequency response, the specified spectral density is approximated by a stepped line with a step of Δ. The best ratio of the step Δ to the passband Δf is a ratio which falls in a range of $0.5 \leqq \Delta/\Delta f \leqq 0.7$.

TThe analysis error, ε_{an}, (the resolution error) is related to the finite selectivity of the analyzing filters, and for this reason, the dispersion at a definite frequency f is usually not measured, but rather the dispersion in the filter passband. It decreases with an increase in the selectivity of the analyzing filters, i.e., it is also a decaying function of the number of control channels.

The statistical error, ε_{stat}, is due to the fact that the duration of signal averaging at the output of the detectors of the analysis block is a finite quantity, i.e., it is the measurement time for the dispersion at the output of the narrow band filters. For the i-th channel, the statistical error is

$$\varepsilon_{\text{стат}} \approx \frac{1}{\sqrt{\Delta f_i T_i}},$$

where T_i is the analysis time. It increases with a reduction in the filter passband, i.e., it is an increasing function of the number of control channels.

The equipment error, ε_{ap}, is due to the error in the channel converters of the control system (vibration measurement conversion, the error in the execution of mathematical operations, the processing of the mismatch signal, etc.) and does not depend on the number of channels.

Thus, the precision in the reproduction of a specified spectral density, $G_x(f)$, is determined by the quality of the generation of the noise signal; the number of generating and analyzing filters; their characteristics (bandwidths, amplitude-frequency response, degree of overlapping, etc.); by the parameters and properties of the averaging devices and the control object; and by the parameters of the multidimensional controller and converters, i.e., by the parameters and properties of the main functional assemblies of the control system.

White noise generators are used as the noise generators in such systems, which make it possible to obtain an electrical noise signal having a homogeneous spectral density of the output voltage (± 1.5 dB) in the requisite frequency range (1-10,000 Hz) with a normal amplitude distribution. The requisite frequency range is shaped by a low pass filter. Sometimes, a high pass filter is used so as to eliminate lower frequencies not included in the working band.

When developing a control system for a random wideband vibration spectrum, the priority task is the efficient selection of the number of channels in the specified frequency range, i.e., the determination of the optimum filter bandpasses and the spectrum analysis time. From an engineering viewpoint, a desirable system is that for which the number of channels and the spectrum analysis time, given a specified system precision, are minimal. However, with a reduction in the number of channels (an increase in the filter passband), the analysis and approximation errors increase, but at the same time, the statistical error falls off; with a reduction in the analysis time, the statistical error increases. Moreover, it should be considered that with an increase in the bandwidth of the analyzing filter, it is necessary to correspondingly reduce the measurement time, and vice versa. In this case, the static error remains constant. In the case of a fixed measurement time, a reduction in the filter bandwidth leads to significant fluctuations in the spectral density, and the statistical reliability of the analysis results is reduced. The averaging interval $T_i \simeq 1/f_{av}$ should be substantially greater than the correlation interval $T_{xi} \simeq 1/2\Delta f$ of the narrow band process, and for this reason, the use of a more narrow band filter leads to the installation of a filter in the averager with a narrower passband, something which is not always permissible or feasible in practice.

To measure the spectral desntiy with a high statistical reliability, the equivalent number of statistical degrees of freedom, $k_{equ} = 2\Delta fT$ should be rather high (400-500). In this case, the statistical ambiguity is equal to 7 and 6.3 percent respectively. It is not reasonable to further increase k_{equ}, since with a substantial increase in k_{equ}, the ambiguity is reduced insignificantly. Knowing k_{equ} and by specifying the passband, one can determine the averaging time, and consequently, the parameters of the filter of the averaging device. However, it is necessary to keep the analysis error in mind.

A filter with a passband of 25 Hz has a high resolution, if $f_0 = 1{,}000$ Hz, but it is useless when $f_0 = 10$ Hz. In the case of a high resolving power of the filter and high statistical reliability, the measurement time is increased, especially at low frequencies. For example, when $f_0 = 20$ Hz, $\Delta f = 0.2$ Hz ($Q = f_0/\Delta f = 100$) and with an 80 percentile confidence range from -7 percent to +9 percent, it amounts to 20 minutes. In this case, a large number of channels (when Q = 4, 20 third-octave filters; when Q = = 20, 100 filters, and when Q = 100, 500 filters) is needed to cover a frequency range of 20-2,000 Hz (Q = const.). For this reason, the ratio $Q = f_0/\Delta f$ should be chosen in an efficient manner. At low frequencies, where the resonances of the objects being tested have a poor Q, the Q of the filters should also be low (2-5); at high frequencies, the Q of the resonances of the objects is considerable, and for this reason, the Q of the filters should be on the order of several tens. In modern 80-channel control systems, which operate in a frequency range of 10-2,000 Hz, Q = 1.5-80.

At the present time, control systems are being produced with 30, 40, 60, 80, 120 and more channels. As a rule, the generating and analyzing filters are identical, and the number of generating filters is equal to the number of analyzing filters. However, the ASDE (of the "Ling" Company, England) and the SARA (France) systems have one filter more in the analysis unit than in the generation unit.

One of the basic components of a control system is the narrow band filter. Filter circuits are diverse. They depend primarily on the frequency range, the requisite passband and the shape of the amplitude-frequency response of the filter. Active and passive filters are used in modern systems. High Q selective RC filters, which have a high selectivity at low frequencies as well are used as active filters. They are distinguished by low size and weight. Active RC filters, which take the form of amplifiers with twin T-bridges, have become the most widespread. Combs of active RC filters make it possible to design compact control systems with a nonuniformity of the spectral density at the equalizer output of ± 1.5 dB. LC filters (crystal and magnetostrictive types also) are used as passive filters.

High Q electromechanical filters have become widely disseminated in recent times. Combs of such filters make it possible to equalize the amplitude-frequency response of the vibrator--product system with a linearity of ±1 dB. However, the control system is substantially complicated in this case, since high frequency filters (100 KHz) are usually employed. For this reason, when generating the spectral density, the spectrum of the working low frequency signal is shifted to the high frequency range by means of modulators, and then back to the low frequency range by demodulators ahead of the control object. As a rule, balanced modulation is employed in such control systems, a distinctive feature of which is the fact that the carrier frequency is absent in the frequency spectrum at the modulator output. In this regard, a carrier frequency is fed to the demodulator input to shift the spectrum to the low frequency range.

A block diagram of a vibration test system with wideband random vibration control using electromechanical filters in shown in Figure 23. A special feature of such a system is the fact that the number of carrier frequency generators in the circuit corresponds to the number of control channels. The difference between the carrier frequencies is determined by the passband of the generating filters and the requirements placed on the precision of the generation of the specified spectrum, in a manner similar to that for systems of a conventional design. Despite the complexity of the circuitry, and the large number of functional components in the system, the latter can be compact. A drawback to the electromechanical filters used in such systems is the poor temperature stability of the frequency.

Crystal filters are employed in the VKV-4500 control system (USSR), and magnetostrictive filters are used in the ARN (of the "Derritron" company, England), the G02-28 (of the"Chinken KO" company, Japan) and other systems.

In all modern random vibration control systems, the acceleration spectral density at the output of the vibrator is determined by measuring the mean value of the dispersion in a narrow band of frequencies. For this, the signal must be passed through a narrow band filter, squared, and integrated (averaged). A typical measurement (analysis) circuit for dispersion contains a linear bandpass filter, a squarer, and averaging and recording devices.

A filter identical to the generating filter of the given control channel is used as the analyzing filter.

The squaring operation is executed with various analog components, which make it possible to obtain the output parameter of the component as a parabolic function of the level present at its input:

$$Z(f) = \gamma y^2(t)$$

where γ is a constant characteristic of the component.

The error of the squaring component is determined by the length of the section over which this function is maintained.

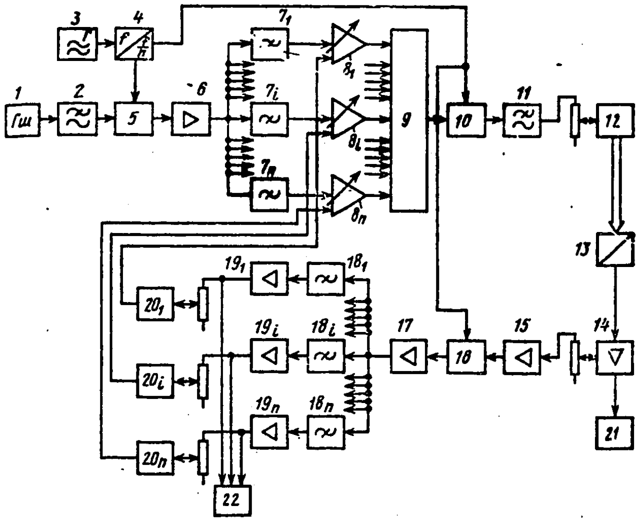


Figure 23. Block diagram of a system for wideband random vibration testing with electromechanical filters.

Key: 1. Noise generator;
2. Low pass filter;
3. High frequency oscillator (carrier);
4. Frequency divider;
5, 16. Modulators;
6, 15, 17, 19. Amplifiers;
7. Shaping filters;
8. Variable gain amplifiers;
9. Mixer;
10. Demodulator;
11. Low pass filter;
12. Vibrational test stand;
13. Vibration transducer;
14. Matching amplifier;
18. Analyzing filters;
20. Automatic gain control;
21. Vibration meter;
22. Spectral density monitor.

Thermocouples, which have a volt-ampere characteristic close to a parabola, are used as the squarers. In this case, the thermcouple is employed in a cathode follower circuit configuration to increase the input impedance of the thermal squarer.

Square-law detectors designed around diode-resistor networks which reproduce the piecewise-linear approximation of the parabolic function have become the most widespread. With a precise approximation of the parabola in the requisite dynamic range (approximately 40 dB), the circuit of such a squarer can be complex and expensive. For the purpose of simplifying the circuit, the square of the mean value is measured instead of the mean square value (the detector of the mean values is a squarer). The systematic error arising in all of the filters is identical. For noise with a normal distribution it is equal to 13 percent and can be taken into account in the scale graduation of the equipment. By an appropriate choice of the discharge time constant τ_d and the charging time constant τ_c of the detector, this error can be reduced to a minimum. For a ratio of $\tau_d/\tau_c = 4$, it is practically absent. An advantage of this circuit is likewise the fact that the mean value detector requires less filtering and is less sensitive to a limited random signal than the square law detector (the low pass filter averaging time constant can be chosen several tens of times less). The signal is fed from the mean value detector to a mean value indicator, a quasi-square-law detector and to the AGC circuit.

To make precise measurements, it is important to efficiently choose the parameters of the averaging device, for which either an integrator or a low pass filter is used. The precision of an integrator is limited by the true time of the measurement, while low pass filter accuracy is also limited by the low pass filter time constant. A low pass filter yields satisfactory results when $T/\tau_f \geq 4$, where T is the measurement time and τ_f is the constant of the low pass filter. With an increase in the low pass filter time constant in the case of measurements of long duration, the averaging error of the low pass filter falls off to the value of the integration error. A low pass filter is significantly simpler than an integrator. It usually takes the form of a passive RC network. An integrator is designed around a direct current amplifier with a high negative feedback level.

Domestic single or multichannel narrow profile meters (M1730, M1635, etc.), graduated in a^2/Hz or a cathode ray tube can be used as the recording device in the monitor units. In this case, the signals from the outputs of the averaging devices are fed to a switcher, which "interrogates" all of the detectors successively, and a sequence of square wave pulses is formed at its output. The pulses are amplified; they can be visually observed on the screen of a cathode ray tube, the sweep of which is synchronized with the switcher rotation. The position of each pulse on the screen corresponds to a specific filter, while the pulse height is proportional to the spectral density in the given frequency range.

When designing a measurement channel, it is essential to take into account the error which arises because of the unequal width of the passbands of the analyzing filters. With an increase in the width of the passband of a filter, the level of the spectral density increases. To reference the spectral density to a constant bandwidth, voltage dividers are provided in the channels in accordance with the relationship: $\sqrt{\Delta f_n/\Delta f_{const}}$.

Light signaling is provided in some models of control devices for operational monitoring of the specified spectral density level.

In modern control devices, besides those instruments which are intended for monitoring the spectral density in the individual channels, there are also instruments for measuring the mean square acceleration throughout the entire working band of frequencies. In this case, a square-law detector is used in the vibration meter, and the vibration meter is graduated in units of vibrational acceleration.

The operational principle of the AGC unit in random vibration control systems is similar to the operational principle of the AGC circuits used in vibration test systems intended for reproducing and controlling sinusoidal vibrations. However, it is the spectral density level in narrow passbands which is regulated in them, and not the sinusoidal signal level. For this reason, besides the vibration measurement transducer and the matching amplifiers, the feedback circuit should contain the corresponding number of narrow band filters (according to the number of system channels), amplifiers, detectors and low pass filters. The components of the analysis circuit are usually employed as these elements.

The basic control section is the variable gain stage, where $K = K(U_y)$, where the signal from the output of the narrow band filter

$$y(t) = A(t)\cos[\omega_0 t + \varphi(t)],$$

is fed to its input, where $\omega_0 = 2\pi f_0$ is the center frequency of the filter; $A(t)$ and $\phi(t)$ are slowly changing functions of time; $A(t)$ is the signal envelope expressed as a Gaussian distribution function and has a frequency spectrum from zero to $\Delta f/2$.

During regulation, the amplitude $A(t)$ should change without changing the distribution function. However, depending on the time constant of the RC low pass filter of the AGC detector, the law governing the distribution of $A(t)$ can change. The actual and the statistical characteristics of the variable gain output stage should obviously not differ during regulation, if the time constant of the regulation circuit is large. However, at large values of the regulation time constant, the equalizer responds excessively slowly to a change in the signal at the vibration test stand.

The lower time limit for system response is determined by the stability conditions, to assure which it is necessary that at any point in time the following condition be met:

$$\frac{H}{\pi \Delta f RC} \leqslant 1,$$

where H is the transfer function of the channel from the output of the shaping filter to the output of the AGC detector; Δf is the passband of the analyzing filter.

An AGC circuit is usually designed so that $\pi \Delta f RC \simeq 20 - 100$. In this case, the probability density of the amplitudes of the output signal of each channel of the equalizer practically does not differ from the Gaussian distribution. If a vacuum tube or semiconductor device is used as the controlled AGC element, then with high level regulation, distortion of the distribution of the instantaneous values of the amplitudes of the noise signal being reproduced can occur. For this reason, it is necessary to use those AGC devices in which the attenuation factor of the voltage divider or attenuator is automatically regulated, rather than the current of the active device (the vacuum tube or transistor). The AGC unit is simplified, and there is no electrical coupling between the circuits of the equalizing device and the AGC unit. Such a circuit has been used, for example, in the domestic SUVU-ShSV-2 system, in which a voltage divider consisting of a resistor and a photoresistor, illuminated by an incandescent lamp, is used as the AGC device.

A specific feature of the AGC device with the photoresistor is the linear response of its volt-ampere characteristic, since the resistance does not depend on the applied voltage, and such a device does not introduce nonlinear distortions. The brightness of the incandescent lamp which lights the photoresistor changes in accordance with the change in the controlling voltage acting at the input to the AGC device.

Systems for the narrow band random vibration testing of products. Vibration test systems intended for reproducing a wideband random vibration make it possible to simulate mechanical effects closest to real effects. The control equipment for such systems is complex and expensive, and for this reason, it is used in large test centers. Under plant conditions, equipment is used which basically makes it possible to simulate wideband random vibration. Vibration test systems which test products using narrow band random vibration with frequency scanning of the signal, are employed for this purpose. These systems are usually built on the same principle as systems for testing with the sweep frequency method. However, instead of a sine wave sweep frequency generator, a special narrow band noise generator is used with scanning of the center frequency, and a functional unit which amplifies the noise signal level by 3 dB/oct depending on the frequency is additionally introduced into the AGC system.

Because of the similarity in the operational principles of the automatic control for sinusoidal and narrow band random vibration, they can structurally be combined in a single instrument. The domestically produced SUVU-USV control system and the 1026 and 1027 control generators of the "Bruele and Koer" Company are designed in this fashion.

Shown in Figure 24 is a block diagram of a system for testing products with narrow band random vibration having a SUVU-USV type control generator. The system operates as follows. A random signal with a normal amplitude distribution and uniform spectral desnity is fed from wideband noise generator 1 to narrow band filter 2 having passbands of 3, 10, 30, and 100 Hz at a frequency of 10 KHz by means of balanced modulator 3 and high frequency sine wave signal generator 4 (40 KHz), the narrow band noise is converted to the

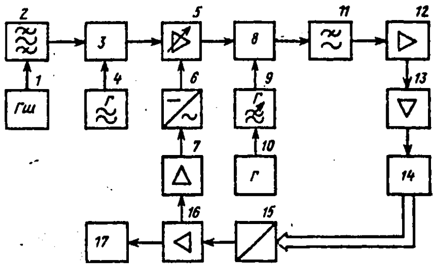


Figure 24. Block diagram of a system for narrow band random vibration testing.

Key: 1. Wideband random noise generator;
2. Narrow band filter;
3. Balanced modulator;
4. High frequency sine wave generator at a fixed frequency;
5. Variable gain amplifier;
6. AGC rectifier;
7. AGC amplifier;
8. Mixer;
9, 10. Variable frequency sine wave generator;
11. Low pass filter;
12. SUVU-3 output amplifier;
13. Power amplifier;
14. Vibrator;
15. Vibration transducer;
16. Matching amplifier;
17. Vibration parameter meter.

range of higher frequencies (50 KHz). The signal is fed from the output of the balanced modulator to the tuned variable gain amplifier 5, the center frequency of the filter of which is tuned to the upper sideband of the signal from the balanced modulator. To generate the low frequency signal in a specified frequency band, mixer 8 is used, to which narrow band noise is fed from the tuned amplifier and the sinusoidal signal from the 50 - 60 KHz variable frequency oscillator (9, 10). The output signal from the mixer is fed to low pass filter 11, where the signal with the difference frequency is isolated. The narrow band noise derived in this manner is fed to the output amplifier of generator 12 and to power amplifier 13, which drives electrodynamic vibrator 14. The mechanical oscillations are converted by vibration transducer 15 and fed through matching amplifier 16 to the vibration parameter 17 and to the input of the AGC block 7.

The dynamic working range of the AGC device is 50 dB. Similar control generators of the "Bruele and Koer" Company, the 1026 and the 1027, have a dynamic control range of 80 - 90 dB. The frequency sweep is accomplished automatically by means of an electric motor. The SUVU-USV generator operates in a frequency range of 5 - 10,000 Hz.

Systems for Mixed Vibration Testing.

There are no specially designed systems for the reproduction of mixed vibration. The systems used at the present time are combination ones, which include the control equipment for harmonic and random vibration. Two conduct the tests using the method of sinusoidal sweep frequency with a wideband signal superimposed on it having a specified spectral density, the "Bruele and Koer" Company recommends putting equipment together in the configuration shown in Figure 25. The sinusoidal excitation signal is generated by the type 1047 controlling generator 4, while the random signal is generated by means of a type 3380 automatic equalizer-analyzer 1,2. The distinctive feature of such a circuit is the presence of the type 2021 heterodyne tracking filter 5 in the feedback circuit, where the sinusoidal signal at the output of the filter is utilized to control the sinusoidal excitation level. The random signal is fed through a bandstop filter, included in the complement of the 2021 instrument, to the compressor input of the equalizer-analyzer to control the spectral density level.

Multichannel Vibration Test Systems

The behavior of a structure when acted upon by vibration depends on the external conditions (for example, the exciting forces, their point of application and frequency) and on the inherent parameters of the structure (weight, stiffness, damping, etc.). The determination of the response of a mechanical structure to the application of a specified external force is the primary task of the dynamic analysis of the structure.

By analyzing the reactions of a simple structure to pulsed or noise excitation, its parameters can be determined in a short time and with sufficient precision. Analysis of the effect of a harmonic force yields good results. The analysis of a complex structure by means of a single vibrator used to excite the harmonic force is possible in those cases where the natural resonant frequencies are spaced significantly far apart, while the deformation of the structure is of a single type.

If the deformation is not of a single type and the structure has rather scattered frequencies and a neglectably small relationship between the deformations, one vibrator does not assure reliable results. The analysis is considerably complicated if the structure has natural resonant frequencies close together and (or) closely related deformations.

In such cases, the mechanical multistage system is reduced to a single stage one by means of choosing that vector of the generalized excitation forces for which the trajectory of motion of the points of the structure have a sinusoidal character (a pure tone). Using additional excitation forces, all

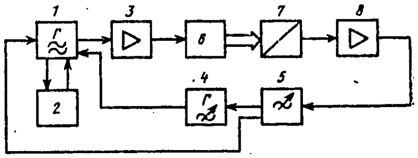


Figure 25. Block diagram of a system for mixed vibration effect testing.

Key:
1. Type 1406 control generator;
2. Equalizer-analyzer;
3. Power amplifier;
4. Type 1047 generator;
5. Type 2021 tracking filter;
6. Vibrator;
7. Vibration transducer;
8. Matching amplifier.

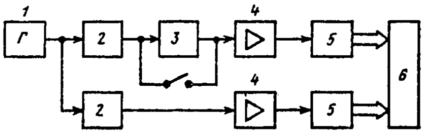


Figure 26. Block diagram of a dual channel vibration test system.

Key:
1. Generator;
2. Attenuator;
3. Inverter;
4. Power amplifier;
5. Vibrator;
6. The product.

of the interfering oscillations are excluded, and the natural resonance frequency, the damping and the generalized mass (or stiffness) are determined for this tone. One of the criteria for the correct choice of the vector of the generalized forces is the absence of phase shifts between the excitation and the oscillation velocity of the individual points of the structure.

Because of the necessity of controlling additional vibrators to excite the additional forces, a multichannel system is required. It is apparent that a system containing several vibrators of the same type, driven by one or several source operating in parallel and controlled by one generator, must be treated as a multichannel system in terms of the equipment used, since it is reduced relatively simply to a system with one vibrator.

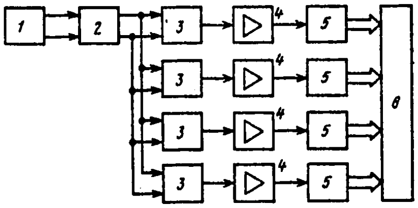


Figure 27. Block diagram of a multichannel vibration test system.

Key:
1. Two-phase generator;
2. Common level and phase control unit;
3. Units for controlling the level and phase of the vibrations of each vibrator;
4. Power amplifier;
5. Vibrators;
6. The product.

Thus, not only the number of vibrators in a multichannel system serves as the criterion for the system, but also the presence of level and phase control for the excited force of each vibrator.

Multichannel systems are employed in the vibration testing of large structures, in studying the natural forms of the oscillations of a structure and to obtain multicomponent vibration.

The simplest multichannel system is a dual channel system, both vibrators of which excite forces which are either in-phase or outeof-phase (Figure 26).

In multichannel systems, it is necessary to control not only the amplitude, but also the phase of the vibrations of each exciter for the purpose of producing in-phase oscillations of the excited structural points of the product being tested. For this, various types of phase shifters are incorporated in each channel system.

The block diagram of a multichannel sytem for studying complex mechanical structurs is shown in Figure 27. The number of channels of this system is determined by the number of vibrators needed to study the structure of the product being tested.

An integral part of a multichannel system is the generators and control devices for the level and phase of the oscillations of each vibrator. These devices can be structurally designed as independent units or as component parts of other blocks of the system.

The level controls usually take the form of either attenuators (controlled or manual), or variable gain amplifiers.

The phase shifters provide for a continuous phase change by ± 180° throughout the entire frequency range. In the case where phase shifters are employed in multichannel vibration test systems, a generator is required which has a two-phase or four-phase output voltage. Phase inverter and integrator generators most completely meet these conditions. Synthesizers, which make it possible to provide for computer control, have recently become increasingly widespread.

The presence of several vibrators and the complexity of the structures being tested determine the multichannel nature of the equipment for the measurement and recording of the vibrations. As a rule, several hundreds of transducers can be mounted on a complex structure, and for this reason, the measurement and recording equipment contains various kinds of switchers. A computer can play the part of the switcher. To set the level and phases at all excitation points, devices are used to simultaneously observe the oscillations at all of these points.

The procedure for the automated control of a specified testing mode is substantially complicated, since it is necessary to track the amplitude and phase of the vibration. In such systems, the amplitude and phase of the oscillations of each vibrator are controlled by means of measuring the in-phase and quadrature components of the oscillation vector, the information on which is rooted to the automatic level and phase control circuitry. The in-phase component is usually regulated by the AGC circuit described earlier. The quadrature component is employed for automatic phase tuning, i.e., to synchronize the oscillations of the vibrators. For this purpose, foriegn companies have developed and are producing special devices: vibration synchronizers, which take the form of automatically controlled phase shifters, which assure the phase agreement of all exciters in the working range of frequencies. For example, the "Chinken KO" Company (Japan) is producing a synchronizer, by means of which the vibrations of four vibrators can be brought into phase. The control oscillators (the 1026 and 1047, etc.) of the "Bruele and Koer" Company can also be used in multichannel vibration systems. A provision is made in them for the capability of adjusting the phase by 360°. In the case of the parallel insertion of several generators of this type in a "master-slave" circuit configuration, one can automatically regulate the amplitude of the oscillations of each vibrator with a multichannel system.

Sometimes, for example, in the case of resonance oscillations or strong couplings between the points where overloads act, even in the case of good synchronization, the influence of adjacent vibrators can lead to system instability and its failure. At frequencies above 200-400 Hz, it is impossible to establish the parameter of a specified testing mode in the case of sinusoidal and random vibrations, and to independently regulate each vibrator of a multichannel system. The causes of this situation are the cross-talk couplings and mutual influence of the various excitation points of the structure. Because of the crosstalk coupling, the overall level of the oscillations at the point being monitored can reach such a value that reducing the input excitation level to it has almost no influence on the overall amplitude of the vibration. Various methods are employed to reduce the influence of cross-talk. For example, to compensate for cross-talk energy one can use a crossed feed of the vibrators (Figure 28). This produces exciter oscillations out of phase with the oscillations resulting from mechanical cross-talk. The cross-talk factor is:

$$cF_{ij} = \frac{V_i}{V_j} \quad (e_i = 0 = a_{ij}),$$

where V_i and V_j are the responses at the i-th and j-th monitor points; a_{ij} is the mechanical transfer function of the crosstalk to the i-th vibrator from the j-th vibrator.

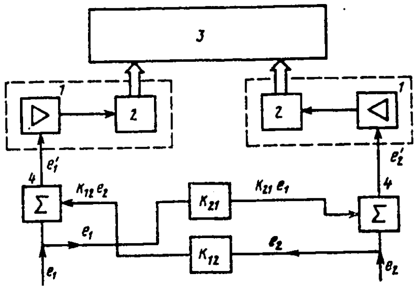
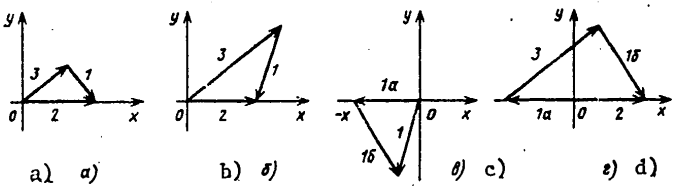


Figure 28. Block diagram of a dual channel vibration test system with compensation for crosstalk energy.

Key: 1. Power amplifiers; 2. Vibrator; 3. The product; 4. Adder: e_i is the electrical signal of the i-th vibrator; K_{ji} is the electrical transfer function of the additional crosstalk supply unit; e_i' is the composite signal of the i-th vibrator.



a) b) c) d)

Figure 29. Diagrams which illustrate the manner of compensation for the crosstalk energy.

The primary task of the crossed feed is to reduce the crosstalk factor cF_{ij} to a value of less than unity, since in this case, the automatic control system operates stably and effectively.

Prior to testing the structure, the crosstalk factors at the control points in the working frequency range are determined beforehand for the case of low excitation levels, and the corresponding gains are set for the cross feed devices driving the exciters.

Another method of compensating for crosstalk energy consists in generating a stabilizing signal from the vibration action applied to the structure from at least one exciter, and in using this signal to control the other exciters, (Figure 29). Vector 1 in Figure 59a represents the amplitude and phase of the force acting on the product from one of the vibrators, vector 3 represents the action of the other vibrators at this point on the product; the resulting action is depicted by vector 2. In Figure 29b, vector 3 is amplified so much vector 1 has a negative component, which corresponds to the removal of power from the product by this vibrator. System operation is unstable in this mode. Shown in Figure 29c is the method of generating an additional vector 1a, which compensates for the negative component vector 1. If it is added to vector 1b, then the result is vector 1, shown in Figure 29b. Vector 1a is the control vector. Its direction is opposite to the direction of the vector of the resulting vibration 2, while its magnitude should be such that vector 1b is always directed to the right, i.e., it should not have a negative component. It is shown in Figure 29d that the vectors 1a, 3 and 1b yield as the sum vector 2, which corresponds to stable system operation thanks to the direction of vector 1b.

TABLE 5

The Technical Chracteristics of Vibrators

System Тип системы Type	1. Тип возбудителя	Максимальная возбуждаемая сила, 2. Н	Максимальная скорость колебаний, 3. м/с	Верхняя граничная частота, 4. Гц	Максимальное перемещение, 5. мм
HS-0151 0,8	—	8 000	0.5	100	50
HS-1005	HE-1100	5 000	1,3		
HS-1010	HE-1200	10 000	0,65		
HS-1020	HE-1300	20 000	1,2	80	100
HS-1050	HE-1500	50 000	1,0		
HS-1100	HE-1600	100 000	0,5		
HS-1500	HE-1800	500 000	0,2	30	

Key:
1. Type of exciter;
2. Maximum excitable force, N;
3. Maximum vibration speed, m/sec;
4. Upper frequency limit, Hz;
5. Maximum travel, mm.

The methods of compensating for crosstalk energy considered above are labor intensive in their execution and require complete automation for wider introduction into vibration testing practice.

Electrohydraulic vibrators are widely used in multichannel systems as the force exciters. Thus, for example, for the vibration testing of motor vehicles and railroad cars, as well as tests for vibrational strength and the experimental determination of the parameters of the natural resonant oscillations in models of buildings and structures, hydraulic installations have been designed by the "Chinken KO" Company (Japan), which are intended for operation in multichannel systems (Table 5).

The "Inova" Company (Czechoslovakia) produces the EDYZ3-n and EDYZ4-n electronic control equipment which is intended for the control of electrodynamic vibrators (1 - 4) during programmable dynamic testing of structures in accordance with a specified law for the change of the acceleration in a frequency range of 0.03 - 300 Hz. The control gear is equipped with a programming unit and a photoelectric device for input from eight-track punched tape.

Structures with distributed parameters (weight, stiffness, damping) are studied by means of multichannel systems. To be numbered among these are first of all complex equipment sets and their structural components, which have a large number of natural resonant oscillation forms. This special feature of the tests produces a number of additional requirements which are placed on multichannel systems intended for studying the natural resonance forms of the oscillations of a structure.

As a rule, the number of channels in such systems is significantly greater than the number of channels in a vibration test system, something which substantially complicates the testing procedure. Stricter requirements are placed on the control equipment as regards the precision in setting the requisite parameters. The level controllers should assure a force setting accuracy with an error of 0.5 percent, and for this reason, multiturn wire potentiometers are frequently used as the level controls as part of a set with multichannel readout devices.

Increased requirements are likewise placed on phase controllers. For example, the error in setting the phase should be less than 0.5 degrees. By using potentiometers and readouts similar to those employed for the level control, these requirements can also be met.

It is essential to reduce the influence of the vibration exciters, the vibrators, on the parameters of the structure and the reaction of the structure to the excitation of the force. For this reason, the vibrators should have a minimal connected mass, while their suspension should have minimal stiffness with respect to the weight and the stiffness of the element of the structure being studied, to which they are connected. These requirements are met by electrodynamic vibrators with a light moving coil, which have a suspension system only for centering the moving system, and which are connected to the structural element by means of light tie rods. To be numbered among the special features of these vibrators are the wide frequency range, beginning at zero, and the high linearity of the characteristic (about 1%):

$F = f(I_n)$, where F is the force which is developed; I_n is the current in the moving coil in a wide dynamic range (less than 60 dB). Moreover, there should be no phase shift between the current in the coil and the pushing force throughout the entire frequency range.

All of the system components should remain linear during excitation. This means, that even at resonant frequencies, the deformation of the structure at any point in it should not exceed the limits of elastic deformation. To obtain such exciting forces at resonant frequencies, vibrators are required having low forces. Thus, for example, vibrators with an output force of 1,000 - 2,000 N are uased to investigate such bulky structures as modern aircraft.

When mechanical oscillations of the structure are present at a natural resonant frequency, the forces developed by the structural components, the mass of which considerably exceeds the mass of the moving system of the vibrator, coincide in phase and level with the force excited by the vibrator at a "reference" point, i.e., with the force which was produced by the mechanical oscillations of this structure. At all the remaining points, the force developed by a structural element can in the general case considerably exceed the force developed by the vibrator positioned at the given point, and may not coincide with it in phase, i.e., the vibrator can be placed in motion by an external force.

In vibrators which operate in a generator mode (forced motion), a voltage is generated which does not match the phase and level of the voltage (or current) of the power amplifier. As a result, the overall voltage (or current) of the power amplifier can differ from the specified value, something which leads to a distortion of the study results.

In order for the moving system not to exert a marked influence on the excitation current with forced oscillations, the output impedance of the amplifier should be high. An amplifier which is a current generator, the output impedance of which amounts to tens of Kohms meets these requirements. The choice of the level and phase of the exciting forces of the vibrators, where the overall number of forces is equal to three, is relatively simple, but becomes considerably complicated when their number increases. The ideal choice is possible only in the case where the excitation points and the directions of the excitation forces are chosen in such a manner that the introduction of any additional exciter, with the appropriate regulation of its force and stiffness (the excitation level and phase) can preclude the excitation of at least one additional tone. The position of the nodes of the interfering tones and the direction of the excitation forces at the start of the testing are not known precisely and are ascertained during the testing process. In those cases where the vibrators excite forces at arbitrary points, the change in the force and stiffness of one vibrator leads to a change in the force and stiffness at the remaining points of the structure. The "Prodera" Company (France) produces 2, 4, 8 and 16 channel equipment, including the power supply equipment, excitation control and recording equipment. It also manufactures the equipment and exciters for studying the structures of an aircraft in flight.

Dual channel equipment is intended for studying comparatively simple assemblies and units (crankshafts, spindles, springs, gear boxes, etc), as well as samples of materials when flexed, twisted or under tension and compression. Tests for wear or rupture with an alternating load can be carried out using this equipment.

Included in the equipment set are a generator and two exciters with power amplifiers. The level control for the common channels is accomplished by the output voltage of the generator, and in each of the channels by the gain of the power amplifiers. The amplifier phase can be varied by 180°. The system is designed in the structural configuration shown in Figure 26.

Such complex structures as motor vehicle compartments, aircraft, engines, etc. can be tested using four channel equipment. Such systems are composed of a two-phase generator, excitation level and phase control units, vibrators, power amplifiers and vibration analysis equipment. This equipment includes vibrations transducers (for travel, velocity or acceleration), a multiphase meter or the simultaneous observation of 20 Lissajous figures, which determine the phase between the exciting force at the characteristic points and the velocity of travel of these points, as well as units for isolating the real and imaginary components of their coordinates.

In some cases, in particular, to study symmetrical structures, four excitation points can be insufficient. Then eight-channel equipment is employed; it includes two sets of four-channel equipment.

A set of eight-channel equipment can include equipment for automatically recording and processing the test results. Sixteen-channel equipment is also put together in a similar fashion, by means of which, one can carry out any kind of investigation.

The 2, 4, 8 and 16-channel systems can be put together with vibrators of different types. Depending on the complexity and the overall dimensions of the structure, and the type of tests, the company recommends vibrators of the following types:

1) When testing for fatigue life and general studies of heavy structures: 20IE20 - EX303; medium structures: EX303 - EX304; light structures: EX304 - 20IE30;
2) For laboratory studies of a rigidly secured structure: 20IE40, and on a breadboard model: 20IE30; in the case of high frequency tests: 20IE20.

The technical characteristics of the vibrators of the "Prodera" company are given in Table 6.

Systems for Multicomponent Vibration Effect Testing

The vibration test systems which have been considered are intended for generating vibrations in one direction. Under actual conditions, the majority of

TABLE 6. The Technical Characteristics of the Vibrators of the "Prodera" Company.

(1) Тип возбудителя	(2) Тип усилителя	Максимальная возбуждаемая сила, (3) Н	Масса подвижной системы, (4) кг	Верхняя граничная частота, (5) Гц	Перемещение, мм (6)
EX-497	494/30	5	0,01	600	5
201E40/C	A-436	10	0,1	300	
EX-304A EX-304C	20WA50ДА A-436		0,032 0,02	200 1000	10
201E40/B	20WA50ДА	35	0,09	2000	5
EX-303A EX-303Д EX-303C	20WA50ДА A-494/30 A-436	50	0,095 0,17 0,15	1400 1130 1000	10
201E20C 201E20B 201E20Д	A-436 20WA50ДА A-438	200	0,32 0,36 0,26	250 200 1000	
EX-356	20WA50ДА+FA	600	1,35	200	
EX-420C EX-420Д	A-438 2XA438	1000	3,0	150 400	12
EX-420E	2XA438	2000	5,0	50	

Key:
1. Type of exciter;
2. Type of amplifier;
3. Maximum excitable force, N;
4. Weight of the moving system, kg;
5. Upper frequency limit, Hz;
6. Travel, mm.

products experience vibration loads in several directions. Vibrations along each axis of an arbitrarily chosen spatial system of coordinates have a different nature of the timewise change and a different degree of cross-correlation between them. For the purpose of having test conditions approximate the actual ones, it is essential to have multicomponent vibration test stands which reproduce the spatial vibration while meeting the requirements presented above.

The motion of a solid in space is determined by six degrees of freedom: three translational degrees in three mutually perpendicular directions and three rotational ones about the coordinate axes of the translational motion.

Test stands which limit the possibilities of the motion of the body to two to three degrees of freedom are usually employed in vibration test systems (translational motion of the body in two to three mutually perpendicular directions or translational motion along one exis in conjunction with rota tion about this axis, etc.). The structural design of the vibrators is considerably complicated with an increase in the number of components. This is related to the necessity of eliminating mutual influence between the individual components, something which is achieved by virtue of substantially complicating the structural design of a vibrator. Moreover, when the number of components is increased, the operational reliability falls off sharply and there arises the necessity of automating the process of controlling and recording the parameters being measured because of the great labor intensity of manual control and recording of the parameters.

Multicomponent vibrators can be electromechanical, electrohydraulic, electrodynamic and mixed types. In accordance with this, the power supply and control equipment for such vibrators is diverse in terms of its composition. It can included control consoles with electric motors, pumps, direct current and alternating current power amplifiers, etc. Such vibrators are usually intended for solving specific problems, and are rearely all-purpose types. As a rule, they have a complex structural design and a limited working range of frequencies and amplitudes.

Two and three component electromechanical type vibrators are known, which generate harmonic oscillations in two to three mutually perpendicular directions in a range of frequencies up to 200 Hz. Dual component electrodynamic type vibrators have been designed which reproduce longitudinal and torsional oscillations independently of each other, in a wide range of frequencies (longitudinal oscillations of 2,000 Hz, angular oscillations of 500 Hz), accelerations (longitudinal oscillations of 750 m/sec^2, angular oscillations of 3,000 deg/sec^2) and displacements (longitudinal displacements of 10 mm, angular, ± 7.5°) in accordance with any specified law. There are individual examples of vibrators which have five to six degrees of freedom and operate in a range of frequencies from 0.1 to 5 Hz with oscillation amplitudes of less than 40 mm.

Of the greatest interest are vibration test systems with multicomponent test stands which consist of single component electrodynamic vibrators having a common vibration platform. A block diagram of a system for reproducing three-component vibration is shown in Figure 30 which used electrodynamic vibrators, which reproduce oscillations in three mutually perpendicular directions on the X, Y and Z axes. The operation of electrodynamic vibrators 6x, 6y and 6z is controlled by master generators 1 or programming racks 2x, 2y and 2z through remote control panel 3. Each vibrator can be controlled from the master units of both types independently of each other. When specifying the vibration from the programming racks, control is realized through a cross correlation instrument for vibration processes, 10, in which the regulation of the cross correlation level of the vibration is accomplished along the X, Y and Z axes. The moving coils of the vibrators are powered from power amplifiers 4x, 4y and 4z. Besides the control equipment, this system includes spectrum analyzers for determining the spectral densities of the vibration accelerations along the axes, as well as spectrum analyzers for the cross-correlation functions 5x, 5y and 5z.

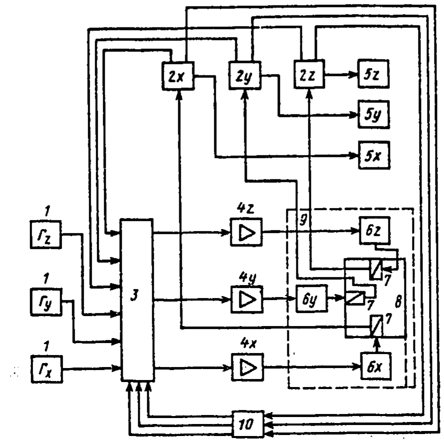


Figure 30. Block diagram of a system for multicomponent vibration testing.

Key:
1. Control generators;
2z,2y,2x. Programming devices;
3. Control panel;
4z,4y,4x. Power amplifiers;
5z,5y,5x. Spectrum analyzers;
6z,6y,6x. Vibrators;
7z,7y,7x. Vibration transducers;
8. Attachment for fastening the product;
9. Bed on which the vibrators are mounted;
10. Cross-correlation instrument for the vibroprocessors.

The signals are fed to the analyzers from transducers 7 through the corresponding meters, which are included in the complement of the programming racks.

The major component of this installation is the vibration platform, the structural design of which precludes mutual influence between components. It is made in the form of a cube or three rigidly fastened, mutually perpendicular walls. The outer surfaces of the vibration platform are coupled through special disks to the vibrators. The surfaces which are adjacent to the platform and the disk are ground and there is a layer of oil between them. Rather great attractive forces (about 1 kgf/cm^2) arise between such surfaces, and at the same time surfaces easily move with respect to one another. The influence of frictional forces is small. It has a pronounced effect only at frequencies below 40 Hz and is absent at frequencies above 100 Hz.

The advantages of the system considered here must include the presence of a wide range of operational parameters, which is basically determined by the technical characteristics of the electrodynamic vibrators used in the system; also, the possibility of testing products in accordance with any specified law; the universality of the system (the possibility of generating a strictly unidirectional, plane or spatial); the possibility of specifying and controlling the cross-correlation; and the absence of the necessity for synchronizing the oscillations for each component.

The Technical Characteristics of the System

The working frequency range, Hz	5 - 3,000
The maximum ejection force of the vibrators, N:	
Vertical	50,000
Horizontal	6,000
The maximum acceleration developed by the vibrators, m/sec^2:	
Vertical	500
Horizontal	300
The maximum amplitude of the vibrations, mm	12
Maximum load lifting capability without additional weighting, kg	70

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CHAPTER 13. SYSTEMS FOR MEASURING AND ANALYZING VIBRATION, SHOCKS AND NOISE

Acoustic Noise Measurements Systems

Acoustic noise measurement systems make it possible to study the effect of acoustic noise on people and equipment, and to monitor and reduce its impact.

The noise level produced by a machine or mechanism depends on many factors, and for this reason, it is recommended that noise be measured under acoustically specified conditions, as indicated in the instruction of the International Standards Organization, the ISO, on technical standards and specifications (ISO, Instruction R495). The acoustic noise power developed by a mechanism can be assessed on the basis of measurement results. When measuring noise, three different types of an acoustic field are usually determined: the acoustically free field, the diffusion field and the semireverberating field.

Noise measurement and analysis systems are primarily used to determine the acoustic properties of a room and improve them; to ascertain the results of the action of acoustic noise on equipment and personnel; in the field of acoustics and communications to evaluate the quality of electrical acoustic devices; and in research in physiological acoustics and acoustic measurements in liquid media.

Acoustic noise measurement and analysis systems can be broken down into two main groups to ascertain the results of the action of noise on equipment and personnel during the operation of equipment and during its testing. Included in the first group are systems consisting of portable and miniature equipment for use in the field, and in the second, complex stationary systems for use in research laboratories.

The simplest measurement system consists of a microphone and a preamplifier, placed on a tripod or stand, in which case, the preamplifier output is coupled to the input of an instrumentation amplifier. The instrumentation amplifiers used in such systems usually contain A, B, C and D equalization circuits. The simplest acoustic noise measurement system is realized in the domestically produced "Shum 1" noise meter, as well as in the SPM101 noise meter (GDR). Such a system can be designed by using the equipment of the "Bruele and Koer" company, for example, the 4145 microphone, the 2819 preamplifier, and the 2606 instrumentation amplifier.

To measure a noise dose, a system is used which takes the form of a combination of a noise meter and a dosimeter or instrumentation amplifier with a dosimeter. Such a system is intended for estimating the equivalent level of continuous sound in accordance with the requirements of domestic and international standards.

The operation of a noise dosimeter is based on the principle of equal energy, i.e. on the hypothesis where an equal noise dose is maintained, a reduction in the sound level by 3 dB is equivalent to doubling its duration. For example, the type 4423 noise dosimeter of the "Bruele and Koer" company operates on this principle. The instrument, incorporated in a system, makes it possible to evaluate the level of continuous sound in accordance with the requirements set forth in ISO recommendations (R1966 and R1999) and in the DIN 45641 standard [German Industrial Standard]. It can also be used to estimate the noise level and impact on people.

The following relationship is the basis for the operation of the 4423 noise dosimeter:

$$L_{\text{экв}} = \frac{q}{\lg 2} \lg\left(\frac{1}{T}\int_0^T \left(\frac{p(t)}{p_0}\right)\frac{20\lg 2}{q}\,dt\right),$$

where $L_{\text{экв}}$ is the equivalent continuous sound level; p(t) is the variable sound pressure; p_0 is a reference pressure, equal to 20 µN/m^2; T is the integration time; q is a parameter which describes the relationship between the sound volume and its permissible duration, chosen equal to three based on ISO and DIN standards.

Under field conditions, the acoustic noise is frequently recorded on magnetic tape by means of portable microphones. The recording is calibrated using a reference signal generated by a sound source using a piston in a closed cylinder [pistonphone] or by an acoustic calibrator. For the purpose of obtaining operationally timely information on the frequency composition of the noise being studied, a spectral analysis of the noise is frequently made with octave or one-third octave filters.

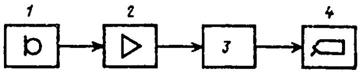

Figure 29. Block diagram of an acoustical noise measurement system.

Key: 1. Microphone;
2. Preamplifier;
3. Frequency spectrometer;
4. Autorecorder.

A noise measurement system with an instrumentation amplifier and a set of bandpass filters permits more precise measurements and noise analysis under steady-state conditions. The 2606, 2607 and 2608 instrumentation amplifiers with the 1613, 1614, 1615 and 1616 bandpass filters (Denmark) can be used in the system. The 2608 and 2609 instrumentation amplifiers are distinguished by a built-in A equalization circuit. The 2606 and 2604 amplifiers contain a peak value detector, a D equalization circuit and allow for the measurement of pulsed sound in accordance with the requirements of the standard DIN 45633, Part II, and the proposals of the International Electrical Engineering Commission. High values of the averaging time and a more refined rectifier circuit are provided in the 2607 amplifier than in the other amplifiers. If it is possible to adjust the level of signal attenuation, for example, by providing for a set of type 1613 filters, then noise level measurements in accordance with a specified noise criterion is simplified, as well as the reading of the maximum permissible noise level in each octave frequency band. The level of attenuation of each filter is adjusted by an amount below the calibration level by which the noise criterion exceeds it. The reading of the noise meter is limited so that the pointer falls below the mark on all of the filters. In this case, it is not necessary to switch the attenuator for the noise meter ranges.

A block diagram of a noise analysis and measurement system with a frequency spectrometer is shown in Figure 29.

The "Messelektronik" People's Enterprise (GDR) recommends that such a system be put together with MK102, MK201 and MK301 microphones, the PS1202 precision sound level meter, the TOA111 one-third octave analyzer and the PSG101 autorecorder. The system makes it possible to record the frequency spectrum of the noise on the chart paper of the autorecorder, in which case, the analyzer is mechanically coupled to the autorecorder. Because of this, one can achieve agreement between the frequencies on the chart paper and the analyzer frequency. The range of frequencies of a system with the MK102 microphone is from 20 Hz to 20 KHz, with the MK201 microphone, it runs from 30 Hz to 35 KHz, and with the MK301 microphone, from 30 Hz to 40 KHz. The one-third octave analyzer makes it possible to analyze noise in a range from 2 Hz up to 160 KHz; the measurable level range runs up to 140 dB.

The 2113 or 2114 frequency spectrometers of the "Bruele and Koer" company (Denmark) can be used in this system, where the center frequencies of the filters of the 2113 instrument fall in a range of 25 Hz up to 20 KHz, while for the 2114 instrument, in a range of 2 Hz to 160 KHz. The passbands can be chosen as octave or one-third octave bands.

For narrow band noise analysis in the field, it is convenient to utilize the 2120 frequency analyzer which is powered from an external 12 volt DC source.

A statistical distribution analyzer, which in conjunction with the level autorecorder makes it possible to obtain acoustic noise histograms, is used in the noise measurement system to study the statistical timewise distribution of the noise levels, as well as the probability of finding noise in a specified range of levels or the noise exceeding a set level.

A system can be designed, for example, using the equipment of the "Bruele and Koer" company by employing the 2305 and 2307 level autorecorders, the 4420 statistical distribution analyzer, the 2606, 2607, 2608 or 2609 instrumentation amplifiers and the 4145 microphone with the 2619 preamplifier. The microphone with the preamplifier is secured to a VA0049 tripod. Such a system is used to measure noise doses using the methods recommended by the ISO.

An analog reader or digital encoder is connected to the level autorecorder for the analog to digital conversion of signal levels. The analog reader provides for a DC output, the level of which is proportional to the mean square, peak, or mean value of the sound signal being measured. The output from the analog reader can be fed to an analog to digital converter, and then to a tape puncher. A digital encoder feeds out data in binary-decimal code, which can be fed to a taper puncher. In stationary systems, wide use is made of noise recording on magnetic tape by means of instrumentation tape recorders or magnetographs.

For the precise determination of the frequency components of noise, for example, when studying acoustic noise produced by machines and mechanisms, stationary systems with narrow band analyzers of two types are used: those with a constant relative or a constant absolute width of the passband.

It is convenient to use an analyzer in real time for the measurement of noise levels, their frequency analysis in octave and one-third octave bands, with visual observation of the results under steady state conditions. In this case, the noise spectrum is displayed directly on the screen of a cathode ray tube as light columns.

For the detailed analysis of audio signals, it is expedient to employ a 3348 real time, narrow band analyzer (of the "Bruele and Koer" company), which contains 400 filters with a constant bandwidth. The spectrum being studied in the selected range is displayed on the screen of the CRT in the form of narrow lines, the number of which is equal to the number of filters. This spectrum is recorded in digital or analog form.

A computer can be employed to estimate the loudness of a sound, and compute the level of the perceived sound in decibels and the sound power.

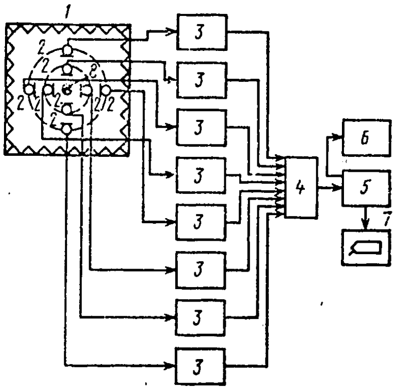

Figure 30. Block diagram of a multichannel system for measuring sound power in an anechoic chamber.

Key:
1. Anechoic chamber;
2. Microphones;
3. Power supplies for the microphones;
4. Channel switcher;
5. Real time analyzer;
6. Analyzer indicator;
7. Level autorecorder;
8. Object being studied.

When measuring pulsed sounds, it is expedient to store the mean signal level and the maximum signal level from the output of the analyzer in real time. In this way, one can study the frequency spectrum following the cessation of the sound pulse. The data from the output of the analyzer are fed to a tape puncher, and then the latter is fed to a computer through a reader.

Multichannel systems are employed to measure the sound power produced by machines and mechanisms, since the sound pressure must be measured at many points in the sound field (Figure 30). The microphones are set up around the machine being studied at design points on the hemisphere and connected through channel switcher 4 to the real time analyzer 5 sequentially, while the results are recorded by autorecorder 7. Based on the recording, the mean values of the sound pressure are determined and the sound power in the individual frequency bands is computed.

A block diagram of a system for determing the sound power is shown in Figure 31, the functioning of which is based on the method of measuring the sound pressure in the diffusion field formed in a reverberation chamber. A computer which is provided with the appropriate program automatically controls the instrumentation system and computes the sound power, taking into account the acoustical qualities of the test chamber and prints the results of the measurement out on a digital printer.

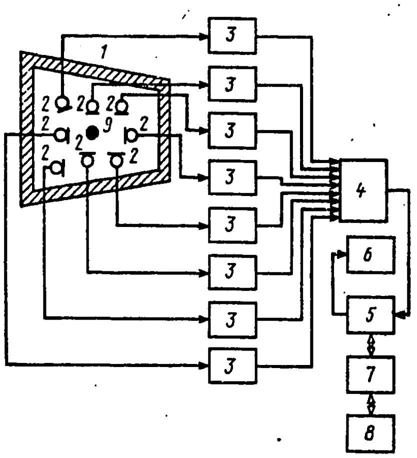

Figure 31. Block diagram of a system for determining the sound power in a reverberation chamber using a computer.

Key:
1. Reverberation chamber;
2. Microphones;
3. Microphone power supplies;
4. Channel switcher;
5. Real time analyzer;
6. Analyzer indicator;
7. Computer;
8. Numerical printer;
9. Object being studied.

In this system, the channel switcher 4 permits the switching of the channels both manually and remotely by means of an external clock generator or the computer 7. Several interconnected channel switchers are used to increase the number of switched channels.

The systems described here can be used to measure pulse noise. In this case, besides the mean square value of the signal level, the positive, negative and maximum peak values are also determined.

When measuring sound shocks, it is expedient to record them on magnetic tape, and then after splicing the individual sections of the tape into a loop, to repeatedly play this recording back for spectral analysis. Instrumentation tape recorders are employed in such systems which permit the analysis of recorded signals with a frequency of down to 0.2 Hz. The signal waveform can be observed on the screen of an oscilloscope or recorded by means of a level autorecorder. In this case, the tape recorder is used as a device which transposes the signal spectrum.

Digital recorders, in particular, the 7502 (of the "Bruele and Koer" company) can be used to measure and analyze short term noise pulses and sound shocks.

This device provides for frequency conversion at a ratio of 1:200,000 when down converting, or a ration of 1:5,000 in the case of up conversion. Analog and digital outputs are provided in the instrument, as well as a device for automatic triggering when the signal exceeds a set level.

In a system for measuring and analyzing short term pulse noise and sound shocks, the microphone is coupled through a microphone system to a digital autorecorder, to the output of which a heterodyne analyzer is connected. The analysis results are recorded by the level autorecorder. A multiplexer can be used to record the signals simultaneously.

A pulse multiplier is connected to the microphone output in systems intended for the determination of the timewise variation in the frequency spectrum of a signal or to isolate frequency components of the signal being studied within specified time intervals. The signal being studied, which is recorded on magnetic tape, which is spliced in a loop, is repeatedly played back by the tape recorder and broken down into short intervals by the pulse multiplier.

A real time frequency analyzer with an autorecorder is connected to the output of the pulse multiplier. Instantaneous spectra can be observed on the screen or an oscilloscope or spectrum analyzer. A three-dimensional frequency spectrum (level--frequency--time) is plotted for the signal being studied based on the results of the analysis.

The "Messelektronik" People's Enterprise (GDR) recommends 10 measurement test stands.

A portable, standard precision sound level meter, the SPM101, with the PF101 monitor sound source, is included in the complement of the first measurement stand. It is suitable for monitoring the noise at industrial enterprises by workers in the labor safety and public health inspectorates.

The PS1202 pulse, precision, portable sound level meter with the PF101 pistonphone is included in the complement of the second measurement test stand. This stand is used in industry, construction, transportation and medicine. The sound level meter is checked and precisely calibrated using the pistonphone.

The third measurement stand is intended for the frequency analysis of noise and contains an additional OF101 octave filter and the ZE322 audio pickup for the determination of the mechanical oscillations of objects in the audio frequency range.

The measurement stand which includes the DSM101 constant sound level meter in addition to the PS1202 and PF101 instruments is intended for production noise monitoring and the comparison of the frequency spectrum of noise produced by mechanisms with the permissible standard values.

The stand which is intended for the equipment of the leading laboratories and has a self-contained power source is a variant of the third stand and provides for the measurement of sound insulation and the propagation of sound waves by the introduction of the SG201 generator, the LV102 power amplifier and a high power sound radiator.

The sixth stand was described in the analysis of the system shown in Figure 29, while the seventh differs from it in that a SBA101 narrow band analyzer is introduced in addition.

The eighth stand is designed for testing in the field of room acoustics and construction acoustics, while the ninth is designed for acoustic instrument checking. This stand is an all-purpose type and contains the equipment of the sixth and eighth stands. The tenth stand serves for the determination of the equivalent constant sound level and the monitoring of the noise level at work positions.

Acoustic noise analysis and measurement systems are used for the production monitoring of series produced products for the noise they generate. Such monitoring is essential in the development of noiseless and low noise products, and to ascertain defects in the product being tested. In this case, it is important to establish permissible noise levels. Since acoustic noise is produced in the majority of cases by vibrations, vibration monitoring is used instead of noise monitoring. Monitoring the level of vibrations is especially effective for mechanisms which operate on shock absorbers, since in this case, the level of interfering vibrations from the operation of other mechanisms is sharply reduced. However, at high frequencies when the number of resonant oscillations of the individual components is high, measurements of the vibrations yield a considerably greater scatter in the readings than measurements of the acoustic noise. For this reason, it is more expedient to monitor both the acoustic noise and vibrations.

Systems have been recently used in practice which permit the monitoring of noise generated in the process of operating machines and mechanisms, and the testing of equipment for the effect of acoustic noise.

The SUAU control system for acoustic installations has been developed in the USSR, where this system is intended for the analysis, generation and automatic maintenance of an acoustic noise spectrum in a one-third octave band of frequencies. The system, with a low frequency amplifier and high power noise sources, forms a closed control loop, which makes it possible to realize the simultaneous setting and analysis of acoustic noise with the output of the measurement results in real time on a screen, a digital display or a computer output, as well as to store the image on a display screen.

The Technical Characteristics of the SUAU System

Bandwidth of the filters	One-third octave
Range:	
of frequencies	From 20 Hz to 20 KHz
of automatic level control, dB	40
of programming, dB, no more than	40
Readouts, dB:	
on a display screen	10, 25 and 50
on a digital display	50

It is expedient to employ such systems in acoustic laboratories to study the influence of high power acoustic noise on equipment, as well when designing equipment to combat noise.
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