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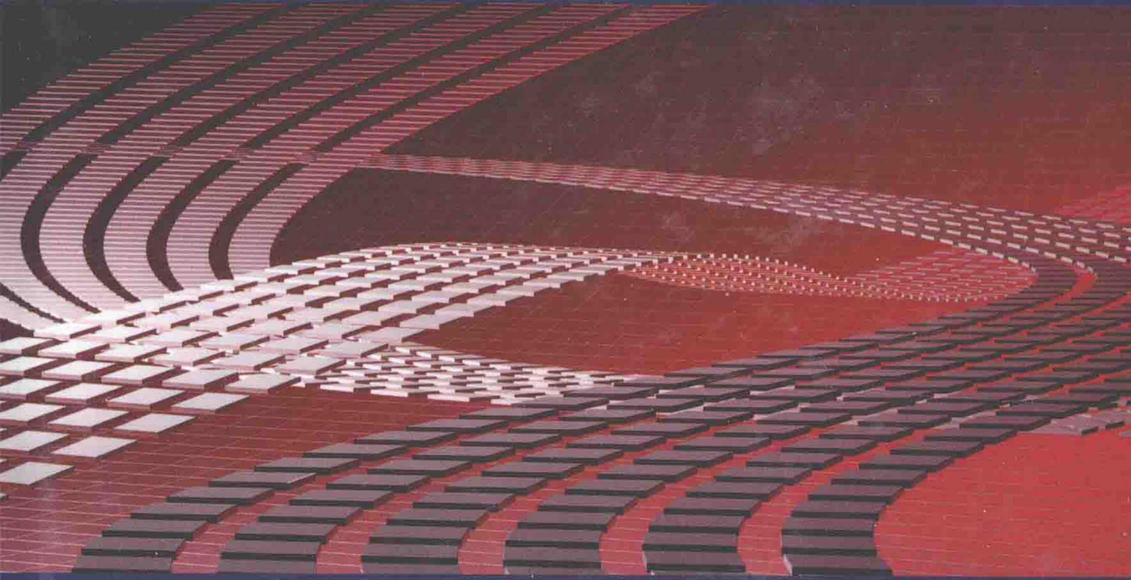

Mechanical Shock

Mechanical Vibration and Shock Analysis
Revised and Updated 3rd Edition
Volume 2

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iSTE

WILEY

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Third edition – Volume 2

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Foreword to Series

In the course of their lifetime simple items in everyday use such as mobile telephones, wristwatches, electronic components in cars or more specific items such as satellite equipment or flight systems in aircraft, can be subjected to various conditions of temperature and humidity, and more particularly to mechanical shock and vibrations, which form the subject of this work. They must therefore be designed in such a way that they can withstand the effects of the environmental conditions to which they are exposed without being damaged. Their design must be verified using a prototype or by calculations and/or significant laboratory testing.

Sizing, and later, testing are performed on the basis of specifications taken from national or international standards. The initial standards, drawn up in the 1940s, were blanket specifications, often extremely stringent, consisting of a sinusoidal vibration, the frequency of which was set to the resonance of the equipment. They were essentially designed to demonstrate a certain standard resistance of the equipment, with the implicit hypothesis that if the equipment survived the particular environment it would withstand, undamaged, the vibrations to which it would be subjected in service. Sometimes with a delay due to a certain conservatism, the evolution of these standards followed that of the testing facilities: the possibility of producing swept sine tests, the production of narrowband random vibrations swept over a wide range and finally the generation of wideband random vibrations. At the end of the 1970s, it was felt that there was a basic need to reduce the weight and cost of on-board equipment and to produce specifications closer to the real conditions of use. This evolution was taken into account between 1980 and 1985 concerning American standards (MIL-STD 810), French standards (GAM EG 13) or international standards (NATO), which all recommended the *tailoring of tests*. Current preference is to talk of the *tailoring of the product to its environment* in order to assert more clearly that the environment must be taken into account from the very start of the project, rather than to check the behavior of the material *a* *posteriori*. These concepts, originating with the military, are currently being increasingly echoed in the civil field.

Tailoring is based on an analysis of the life profile of the equipment, on the measurement of the environmental conditions associated with each condition of use and on the synthesis of all the data into a simple specification, which should be of the same severity as the actual environment.

This approach presupposes a proper understanding of the mechanical systems subjected to dynamic loads and knowledge of the most frequent failure modes.

Generally speaking, a good assessment of the stresses in a system subjected to vibration is possible only on the basis of a finite element model and relatively complex calculations. Such calculations can only be undertaken at a relatively advanced stage of the project once the structure has been sufficiently defined for such a model to be established.

Considerable work on the environment must be performed independently of the equipment concerned either at the very beginning of the project, at a time where there are no drawings available, or at the qualification stage, in order to define the test conditions.

In the absence of a precise and validated model of the structure, the simplest possible mechanical system is frequently used consisting of mass, stiffness and damping (a linear system with one degree of freedom), especially for:

– the comparison of the severity of several shocks (shock response spectrum) or of several vibrations (extreme response and fatigue damage spectra);

– the drafting of specifications: determining a vibration which produces the same effects on the model as the real environment, with the underlying hypothesis that the equivalent value will remain valid on the real, more complex structure;

– the calculations for pre-sizing at the start of the project;

– the establishment of rules for analysis of the vibrations (choice of the number of calculation points of a power spectral density) or for the definition of the tests (choice of the sweep rate of a swept sine test).

This explains the importance given to this simple model in this work of five volumes on "Mechanical Vibration and Shock Analysis".

Volume 1 of this series is devoted to *sinusoidal vibration*. After several reminders about the main vibratory environments which can affect materials during their working life and also about the methods used to take them into account, following several fundamental mechanical concepts, the responses (relative and absolute) of a mechanical one-degree-of-freedom system to an arbitrary excitation are considered, and its transfer function in various forms are defined. By placing the properties of sinusoidal vibrations in the contexts of the real environment and of laboratory tests, the transitory and steady state response of a single-degree-of-freedom system with viscous and then with non-linear damping is evolved. The various sinusoidal modes of sweeping with their properties are described, and then, starting from the response of a one-degree-of-freedom system, the consequences of an unsuitable choice of sweep rate are shown and a rule for choice of this rate is deduced from it.

Volume 2 deals with *mechanical shock*. This volume presents the shock response spectrum (SRS) with its different definitions, its properties and the precautions to be taken in calculating it. The shock shapes most widely used with the usual test facilities are presented with their characteristics, with indications how to establish test specifications of the same severity as the real, measured environment. A demonstration is then given on how these specifications can be made with classic laboratory equipment: shock machines, electrodynamic exciters driven by a time signal or by a response spectrum, indicating the limits, advantages and disadvantages of each solution.

Volume 3 examines the analysis of *random vibration* which encompasses the vast majority of the vibrations encountered in the real environment. This volume describes the properties of the process, enabling simplification of the analysis, before presenting the analysis of the signal in the frequency domain. The definition of the power spectral density is reviewed, as well as the precautions to be taken in calculating it, together with the processes used to improve results (windowing, overlapping). A complementary third approach consists of analyzing the statistical properties of the time signal. In particular, this study makes it possible to determine the distribution law of the maxima of a random Gaussian signal and to simplify the calculations of fatigue damage by avoiding direct counting of the peaks (Volumes 4 and 5). The relationships, that provide the response of a one-degree-of-freedom linear system to a random vibration, are established.

Volume 4 is devoted to the calculation of *damage fatigue*. It presents the hypotheses adopted to describe the behavior of a material subjected to fatigue, the laws of damage accumulation and the methods for counting the peaks of the response (used to establish a histogram when it is impossible to use the probability density of the peaks obtained with a Gaussian signal). The expressions of mean damage and its standard deviation are established. A few cases are then examined using other hypotheses (mean not equal to zero, taking account of the fatigue limit, non-linear accumulation law, etc.). The main laws governing low cycle fatigue and fracture mechanics are also presented.

Volume 5 is dedicated to presenting the method of *specification development* according to the principle of tailoring. The extreme response and fatigue damage spectra are defined for each type of stress (sinusoidal vibrations, swept sine, shocks, random vibrations, etc.). The process for establishing a specification as from the lifecycle profile of the equipment is then detailed taking into account the uncertainty factor (uncertainties related to the dispersion of the real environment and of the mechanical strength) and the test factor (function of the number of tests performed to demonstrate the resistance of the equipment).

First and foremost, this work is intended for engineers and technicians working in design teams responsible for sizing equipment, for project teams given the task of writing the various sizing and testing specifications (validation, qualification, certification, etc.) and for laboratories in charge of defining the tests and their performance following the choice of the most suitable simulation means.

Introduction

Transported or on-board equipment is very frequently subjected to mechanical shocks in the course of its useful lifetime (material handling, transportation, etc.). This kind of environment, although of extremely short duration (from a fraction of a millisecond to a few dozen milliseconds), is often severe and cannot be ignored.

The initial work on shocks was carried out in the 1930s on earthquakes and their effect on buildings. This resulted in the notion of the shock response spectrum. Testing on equipment started during World War II. Methods continued to evolve with the increase in power of exciters, making it possible to create synthetic shocks, and again in the 1970s, with the development of computerization, enabling tests to be directly conducted on the exciter employing a shock response spectrum.

After a brief recapitulation of the shock shapes most often used in tests and of the possibilities of Fourier analysis for studies taking account of the environment (Chapter 1), Chapter 2 presents the shock response spectrum with its numerous definitions and calculation methods.

Chapter 3 describes all the properties of the spectrum showing that important characteristics of the original signal can be drawn from it, such as its amplitude or the velocity change associated with the movement during the shock.

The shock response spectrum is the ideal tool for drafting specifications. Chapter 4 details the process which makes it possible to transform a set of shocks recorded in the real environment into a specification of the same severity, and presents a few other methods proposed in the literature.

Knowledge of the kinematics of movement during a shock is essential to the understanding of the mechanism of shock machines and programmers. Chapter 5 gives the expressions for velocity and displacement, according to time, for classic shocks, depending on whether they occur in impact or impulse mode.

Chapter 6 describes the principle of the shock machines currently most widely used in laboratories and their associated programmers. To reduce costs by restricting the number of changes in test facilities, specifications expressed in the form of a simple shock (half-sine, rectangle, sawtooth with a final peak) can occasionally be tested using an electrodynamic exciter. Chapter 7 sets out the problems encountered, stressing the limitations of such means, together with the consequences of modification, that have to be made to the shock profile, on the quality of the simulation.

Determining a simple-shaped shock of the same severity as a set of shocks, on the basis of their response spectrum, is often a delicate operation. Thanks to progress in computerization and control facilities, this difficulty can occasionally be overcome by expressing the specification in the form of a response spectrum and by controlling the exciter directly from that spectrum. In practical terms, as the exciter can only be driven with a signal that is a function of time, the software of the control rack determines a time signal with the same spectrum as the specification displayed. Chapter 8 describes the principles of the composition of the equivalent shock, gives the shapes of the basic signals most often used, with their properties, and emphasizes the problems that can be encountered, both in the constitution of the signal and with respect to the quality of the simulation obtained.

Pyrotechnic devices or equipment (cords, valves, etc.) are very frequently used in satellite launchers due to the very high degree of accuracy that they provide in operating sequences. Shocks induced in structures by explosive charges are extremely severe, with very specific characteristics. Their simulation in the laboratory requires specific means, as described in Chapter 9.

Containers must protect the equipment carried in them from various forms of disturbance related to handling and possible accidents. Tests designed to qualify or certify containers include shocks that are sometimes difficult or even impossible to produce given the combined weight of the container and its content. One relatively widely used possibility consists of performing shocks on scale models, with scale factors of the order of 4 or 5, for example. This same technique can be applied, although less frequently, to certain vibration tests. At the end of this volume, the Appendix summarizes the laws of similarity adopted to define the models and to interpret the test results.

List of Symbols

The list below gives the most frequent definition of the main symbols used in this book. Some of the symbols can have another meaning locally which will be defined in the text to avoid any confusion.

a_{max}	Maximum value of $a(t)$
$a(t)$	Component of shock $\ddot{x}(t)$
A_c	Amplitude of compensation signal
$A(\theta)$	Indicial admittance
b	Parameter b of Basquin's relation $N\,\sigma^b = C$
c	Viscous damping constant
C	Basquin's law constant ($N\,\sigma^b = C$)
$d(t)$	Displacement associated with $a(t)$
D	Diameter of programmer
$D(f_0)$	Fatigue damage
e	Neper's number
E	Young's modulus or energy of a shock
ERS	Extreme response spectrum
$E(t)$	Function characteristic of swept sine
f	Frequency of excitation
f_0	Natural frequency
$F(t)$	External force applied to system
F_{rms}	Rms value of force
F_m	Maximum value of $F(t)$
g	Acceleration due to gravity
h	Interval (f/f_0) or thickness of the target
$h(t)$	Impulse response
H	Drop height
H_R	Height of rebound
$H(\ )$	Transfer function
i	$\sqrt{-1}$
IPS	Initial peak sawtooth
$\Im(\Omega)$	Imaginary part of $\ddot{X}(\Omega)$
k	Stiffness or coefficient of uncertainty
K	Constant of proportionality of stress and deformation
ℓ_{rms}	Rms value of $\ell(t)$
ℓ_m	Maximum of $\ell(t)$
$\ell(t)$	Generalized excitation (displacement)

$\dot{\ell}(t)$	First derivative of $\ell(t)$
$\ddot{\ell}(t)$	Second derivative of $\ell(t)$
L	Length
$L(\Omega)$	Fourier transform of $\ell(t)$
m	Mass
n	Number of cycles undergone by test-bar or material
n_{FT}	Number of points of the Fourier transform
N	Number of cycles to failure
p	Laplace variable or percentage of amplitude of shock
q_0	Value of $q(\theta)$ for $\theta = 0$
$\dot{q}_0$	Value of $\dot{q}(\theta)$ for $\theta = 0$
$q(\theta)$	Reduced response
$\dot{q}(\theta)$	First derivative of $q(\theta)$
$\ddot{q}(\theta)$	Second derivative of $q(\theta)$
Q	Q factor (quality factor)
$Q(p)$	Laplace transform of $q(\theta)$
r(t)	Time window
R_e	Yield stress
R_m	Ultimate tensile strength
$R(\Omega)$	Fourier transform of the system response
$\Re(\Omega)$	Real part of $\ddot{X}(\Omega)$
s	Standard deviation
S	Area
SRS	Shock response spectrum
STFT	Short term Fourier transform
S( )	Power spectral density
t	Time
t_d	Decay time to zero of shock
t_i	Fall duration
t_r	Rise time of shock
t_R	Duration of rebound
T	Vibration duration
T_0	Natural period
TPS	Terminal peak sawtooth
$u(t)$	Generalized response
$\dot{u}(t)$	First derivative of $u(t)$
$\ddot{u}(t)$	Second derivative of $u(t)$
v_f	Velocity at end of shock
v_i	Impact velocity
v_R	Velocity of rebound
$v(t)$	Velocity $\dot{x}(t)$ or velocity associated with $a(t)$
V( )	Fourier transform of $v(t)$
x_m	Maximum value of $x(t)$
$x(t)$	Absolute displacement of the base of a one-degree-of-freedom system
$\dot{x}(t)$	Absolute velocity of the base of a one-degree-of-freedom system
$\ddot{x}(t)$	Absolute acceleration of the base of a one-degree-of-freedom system
$\ddot{x}_{rms}$	Rms value of $\ddot{x}(t)$
$\ddot{x}_m$	Maximum value of $\ddot{x}(t)$
$\ddot{X}_m$	Amplitude of Fourier transform $\ddot{X}(\Omega)$
$\ddot{X}(\Omega)$	Fourier transform of $\ddot{x}(t)$
$y(t)$	Absolute response of displacement of mass of a one-degree-of-freedom system
$\dot{y}(t)$	Absolute response velocity of the mass of a one-degree-of-freedom system
$\ddot{y}(t)$	Absolute response acceleration of mass of a one-degree-of-freedom system
z_m	Maximum value of $z(t)$
z_s	Maximum static relative displacement
z_{sup}	Largest value of $z(t)$

$z(t)$	Relative response displacement of mass of a one-degree-of-freedom system with respect to its base
$\dot{z}(t)$	Relative response velocity
$\ddot{z}(t)$	Relative response acceleration
α	Coefficient of restitution
δt	Temporal step
$\delta(t)$	Dirac delta function
ΔV	Velocity change
ϕ	Dimensionless product $f_0\ \tau$
$\phi(\Omega)$	Phase
η	Damping factor of damped sinusoid
η_c	Relative damping of compensation signal
$\lambda(\ )$	Reduced excitation
$\Lambda(p)$	Laplace transform of $\lambda(\ )$
π	3.14159265...
θ	Reduced time ($\omega_0\ t$)
θ_d	Reduced decay time
θ_m	Reduced rise time
θ_0	Value of θ for $t = \tau$
ρ	Density
σ	Stress
σ_{cr}	Crushing stress
σ_m	Maximum stress
τ	Shock duration
τ_1	Pre-shock duration
τ_2	Post-shock duration
τ_{rms}	Rms duration of a shock
ω_c	Pulsation of compensation signal
ω_0	Natural pulsation ($2\ \pi\ f_0$)
Ω	Pulsation of excitation ($2\ \pi\ f$)
ξ	Damping factor

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