Development of multivariate equivalent cyclic tests of HALT-based aviation radio equipment for assessing reliability

V E Trushnikov¹, A V Komissarov², M V Grishin³

¹Doctor of Technical Sciences, Professor, Professor of the Department of System Analysis and Management, St. Petersburg Mining University, St. Petersburg
²Chief designer of Ulyanovsk Instrument Design Bureau JSC, Ulyanovsk
³Ph.D., Designing engineer of Ulyanovsk Instrument Design Bureau JSC, Ulyanovsk

E-mail: Trushnikov_VT@pers.spmi.ru

Abstract: The article studies forced test models for determining reliability of on-board electronic equipment due to the combined effects of broadband random vibration and cyclical changes in temperature. The model of multivariate equivalent cyclic tests based on HALT (High accelerated life / limited test) procedures is described.

1. Introduction

In [1], the authors described the main methods for assessing reliability of civilian avionics. The urgent task is to develop a mathematical model of multivariate equivalent cyclic tests based on the characteristics of test equipment and procedures for conducting highly accelerated life (limit) rejection High accelerated life / limited tests [2]. Simulation of the effects of external factors using CAE-system software packages (ANSYS, ABAQUS, NASTRAN, MARC, Asonika, etc.) is based on reference and experimental (exploration) data which cause an inadequate assessment of reliability of the on-board electronic equipment.

Several sources provide options for using HALT procedures to assess the level of reliability (application of the electronic component base, design flaws, imperfections in technological operations and errors during their implementation in production, etc.) of on-board radio-electronic equipment and determine the resource indicator (reliability) of the product. The basic concept is based on the theory of fatigue accumulation.

Table 1. The model for describing forced factors.

| Acceleration factor                                      | Basic model                        | Test model                                |
|----------------------------------------------------------|------------------------------------|-------------------------------------------|
| Cyclic changes in temperature                            | Arrhenius equation                 | $0.0833 \cdot \left( \frac{\Delta T_{HALT}}{\Delta T_{oscillations}} \right)^{-k}$ |
| The cyclic rate of temperature changes                   | Coffin-Manson Equation             | $\left( \frac{V_{\Delta T_{HALT}}}{V_{\Delta T_{oscillations}}} \right)^{1/3}$ |
| Multi-axis broadband random vibration                    | Basquin equation                   | $\sqrt{(G_{xx}+G_{yy}+G_{zz})^b}$          |
| Electrical loads                                         | The ratio of the number of on and off modes for a period of time | $\frac{N_{HALT}}{N_0}$                     |

The paper [3] describes the test equivalence model in which the limiting state during the cyclic exposure to forcing factors is the excess of a certain level of performance parameters as a result of accumulation of residual (fatigue) effects, while the mechanism of development of such effects does not make a decisive difference (phenomenological model).
The moment of achieving the limit state depends on the exposure parameters and properties of the product. The criterion combining these factors is the impact energy $E$ required to reach the limit state during $T_L$. The following expressions are used for non-stationary (1) and stationary (2) random effects:

$$ E = \int_0^{T_L} D(t) dt $$  \hspace{1cm} (1)

$$ E = D T_L $$  \hspace{1cm} (2)

The impact energy applied to achieve the limit state of the product serves as the aggregate characteristic of the limit values of its destruction parameters. The convenience of the energy approach is due to the fact that the nature of the impact is not of fundamental importance; however, this takes into account both properties of the impact and properties of the product structure, thereby describing the stress state. This feature allows for the justification of equivalent tests [4].

2. The model of impact of the broadband random vibration

The concept of design models of the resource involves two main approaches to vibration exposure [5]:

1. The model of multi-cycle fatigue described by the Basquin equation:

$$ \frac{\Delta \sigma}{2} = \sigma_f \left(2N_f\right)^b $$  \hspace{1cm} (4)

where $\Delta \sigma/2$ - voltage amplitude per cycle; $N_f$ - the number of cycles before destruction; $\sigma_f$ – the fatigue coefficient and $b$ – material dependent fatigue strength (Basquin indicator).

In practice, the empirical relation developed by S. Crandl and W. Mark has gained wider application:

$$ N_f = N_b \left(\frac{\sigma_0}{\sigma_d}\right)^m $$  \hspace{1cm} (5)

where $N_f$ – the number of cycles before destruction; $N_b$ – the basic number of cycles; $\sigma_0$ - fatigue limit;
$\sigma_d$ - voltage amplitude per cycle; $m$ – the material dependent parameter.

The low-cycle fatigue model described by the Manson-Coffin-Basquin equation:

$$ \frac{\Delta \sigma}{2} = \frac{\sigma_f}{E} \left(2N_f\right)^b + \epsilon_f \left(2N_f\right)^c $$  \hspace{1cm} (6)

where $\Delta \sigma/2$ - the amplitude of total deformation in the cycle; $N_f$ - the number of cycles before the destruction; $\sigma_f$ - the fatigue coefficient, $b$ - Basquin’s exponent, $\epsilon_f$ - the fatigue ductility coefficient; $c$ the indicator of fatigue ductility depending on the material; $E$ - the modulus of elasticity.

The fatigue model is the accumulation of damage characterized by the monotonous irreversible achievement of the ultimate state (failure) due to the summation of relative damage described by the Miner hypothesis of linear accumulation (it is assumed that complete destruction is achieved at $D = 1$):

$$ D = \sum_{i=1}^{n} \frac{n_i(S_i)}{N_i(S_i)} $$  \hspace{1cm} (7)

where $D_i$ - accumulated fatigue damage during the stress $S_i$; $n_i$ - the number of stress cycles on load with amplitude $S_i$; $N_i$ – the number of stress cycles with amplitude $S_i$ before the destruction.

[6] describes the effect of multiaxial vibration used in tests using the HALT / HASS techniques (Figure 1).
It was proved that the method of conducting equivalent cyclic tests under the sequential action of broadband random vibration along each axis does not interpret the exploratory mode. A comparative analysis conducted by ESPEC Qualmark (USA) showed that HALT multiaxial vibration tests provide a greater energy impact than traditional tests, for example, NAVMAT-9492 tests (Figure 2).

Using the Huber-Mises energy theory for simulating the test process and taking into account the zero excitation of the vibration table, the voltage power spectrum equivalent to the multiaxial vibration mode can be presented as follows [7]:

\[ G_M = G_{xx} + G_{yy} + G_{zz} + 3(G_\Theta + G_\Psi + G_\Phi) \]

where \( G_{xx}, G_{yy}, G_{zz} \) - voltage power spectra along each axis X, Y and Z, \( G_\Theta, G_\Psi, G_\Phi \) - rotation voltage power spectra. The value of the parameter of accumulation of fatigue damage during the multiaxial vibration DM in expression (9) is many times higher than the fatigue accumulated during the sequential test mode along each axis \( D_s \) in expression (8):

\[ D_s = \sqrt{G_{xx}^b + G_{yy}^b + G_{zz}^b} \] (8)

\[ D_M = \sqrt[3]{\left(G_{xx} + G_{yy} + G_{zz} + 3(G_\Theta + G_\Psi + G_\Phi)\right)^b} \] (9)

Studies of the effect of power spectra of rotational stresses on fatigue damage to products require more detailed experimental data to build theoretical models of fatigue accumulation [8]. Hence, neglecting the energy of rotation during multiaxial vibration, we obtain the fatigue accumulation parameter during testing in the HALT chamber.
The maximum exploratory level of spectral density, taking $G_{\text{exp} \text{max}} = G_{xx} = G_{yy} = G_{zz}$ and:

$$D_{\text{Expt}} = 3 \sqrt[3]{G_{\text{exp} \text{max}}} b \tag{11}$$

The equivalence of tests is the equality of the energy of the impact of exploratory loads during the assigned resource to the energy of the impact of tests. Assuming that the exposure energies during the tests in the HALT chamber and the exposure energies during the exploration are equal, taking into account expressions (7) and (10) for the spectral power density and the equality of the accumulated fatigue parameter, we have the following expression

$$\frac{T_{\text{exp}}}{T_t} = \frac{3 \sqrt{G_{\text{exp} \text{max}} b}}{\sqrt{G_{xx} + G_{yy} + G_{zz}}} \tag{12}$$

The acceleration factor is

$$F_{Vibration} = \frac{3 \sqrt[3]{G_{\text{exp} \text{max} t}}}{\sqrt{G_{xx} + G_{yy} + G_{zz}}} \tag{13}$$

The parameter $b$ for electronic devices is usually chosen in the range from 3 to 8 [4]. Recent studies of reliability of electronic components in BGA and CMS packages give a parameter value of 4 to 6 [9]. Moreover, according to Table G.1, the mode of the basic operation cycle in terms of vibration exposure is divided into different periods depending on the duration of exposure and location on board [4] (Figure 3).

Fig. 3. Typical layout of avionics
The test time for each exploring mode \( N \) is calculated by expression:

\[
T_{\text{HALT}} = \sum_{i=1}^{N} T_{\text{exp}i} \left( \frac{G_{\text{expt max}}}{G_{\text{expt}i}+G_{\text{yy}}+G_{\text{zz}}} \right)^{b} \]  \hspace{1cm} (14)

3. The effect of cyclic changes in temperature

For equivalent tests of on-board electronic equipment in a functional mode, the following formula of the base year of operation is used to calculate the number of test cycles for cyclic temperature changes [4]:

\[
N_{\text{ERE}} = \sum_{i=1}^{12} N_{i} = N_{t} \sum_{i=1}^{12} 0.0833 \cdot \left( \frac{\Delta T_{\text{HALT}}}{\Delta T_{\text{oscil}i}} \right)^{-k} \]  \hspace{1cm} (15)

where \( N_{t} \) - the number of test cycles per month; \( N_{i} \) - the number of take-offs / landings per year; \( \Delta T_{\text{HALT}} \) - the absolute value of the range of temperature changes during testing; \( \Delta T_{\text{oscil}i} \) - the range of fluctuations in temperature in the aircraft compartment per month; the longevity line slope coefficient \( k \) is equal to 6 in the test mode equivalent to the flight mode.

However, in expression 15, the rate of changes in temperature oscillations during testing \( V_{\Delta T_{\text{HALT}}} \) and operation \( V_{\Delta T_{\text{oscil}}} \) is not taken into account [4, 5, 12]

\[
N_{\Delta T} = \left( \frac{V_{\Delta T_{\text{HALT}}}}{V_{\Delta T_{\text{oscil}}}^i} \right)^{1/3} \]  \hspace{1cm} (15)

For the base year of operation, expression (15) is as follows:

\[
N_{\text{ERE}} = N_{t} \sum_{i=1}^{12} 0.0833 \cdot \left( \frac{\Delta T_{\text{HALT}}}{\Delta T_{\text{oscil}i}} \right)^{-k} \times \left( \frac{V_{\Delta T_{\text{HALT}}}}{V_{\Delta T_{\text{oscil}}}^i} \right)^{1/3} \]  \hspace{1cm} (16)

For equivalent tests of on-board electronic equipment in aircraft storage modes during the year:

\[
N_{\text{ESM}} = \sum_{i=1}^{12} N_{s_{i}} \left( \frac{\Delta T_{\text{HALT}}}{\Delta T_{s_{i}}} \right)^{-k} + \left( \frac{\Delta T_{\text{HALT}}}{\Delta T_{s_{i}}^{\text{c}}} \right)^{-k} \]  \hspace{1cm} (17)

where \( N_{s_{i}} \) - number of test cycles per one month; \( \Delta T_{\text{HALT}} \) - the absolute value of the range of temperature changes during testing; \( \Delta T_{s_{i}} \) - the absolute value of the range of changes in storage temperature per day, the difference between day and night temperatures \( \Delta T_{s_{i}} = T_{s_{i}} - T_{s_{i}}^{\text{m}} \); \( \Delta T_{s_{i}}^{\text{c}} \) - the absolute value of the range of changes in storage temperatures per year, the difference between the maximum value and the minimum temperature \( \Delta T_{s_{i}} = T_{s_{i}}^{\text{m}} - T_{s_{i}}^{\text{m}} \).

Given the rate of temperature changes during testing \( V_{\Delta T_{\text{HALT}}} \), the rate of changes during the day \( V_{\Delta T_{\text{oscil}i}} \) and the year \( V_{\Delta T_{\text{oscil}i}}^{\text{c}} \), let the number of test cycles per 1 storage year be

\[
N_{\text{ESM}} = \sum_{i=1}^{12} N_{s_{i}} \left[ \left( \frac{\Delta T_{\text{HALT}}}{\Delta T_{s_{i}}} \right)^{-k} \left( \frac{V_{\Delta T_{\text{HALT}}}}{V_{\Delta T_{s_{i}}}^{\text{c}}} \right)^{1/3} \right] + \left( \frac{\Delta T_{\text{HALT}}}{\Delta T_{s_{i}}^{\text{c}}} \right)^{-k} \times \left( \frac{V_{\Delta T_{\text{HALT}}}}{V_{\Delta T_{s_{i}}^{\text{c}}}^{\text{c}}} \right)^{1/3} \]  \hspace{1cm} (18)

The acceleration factor under transportation mode tests:

\[
F_{\text{transp}} = \left( \frac{\Delta T_{\text{HALT}}}{\Delta T_{\text{transp}}} \right)^{-k} \times \left( \frac{V_{\Delta T_{\text{HALT}}}}{V_{\Delta T_{\text{oscil}}}^{\text{c}}} \right)^{1/3} \]  \hspace{1cm} (19)

4. The electric load model

The model of electrical loads is a uniform distribution of the on (during heating) and off (during cooling) modes during each testing cycle for cyclic changes in temperature and heat shock. The initial data for developing the calculated model of electrical loads are as follows: the average flight duration during one day \( T_{p} \), the average annual flight \( T_{d} \), the average annual number of flights (takeoffs and landings) \( N_{f} \) which determines the number of on and off modes, \( N_{h} \) - the number of on / off modes for the entire time of operation, including the routine maintenance work according to the technical documents.

The calculated value of the acceleration factor is determined by the following ratio:
\[ F_E = \frac{N_I}{N_E} \]
\[ N_E = N_P + N_R + 1 \]
\[ N_P = 2 \cdot N_{V-p} \text{ or } N_{II} = \frac{T_{SH}}{365} \cdot \frac{2}{T_P} \]

For one year
\[ N_R = 2 \cdot \left( \frac{T_Y}{T_{DY}} + \frac{T_Y}{24 \cdot T_{WY}} + 3,65 \cdot \frac{T_Y}{T_A} \right) \]

5. The model of the combined impact of factors

[9] studies the simultaneous influence of broadband random vibration and cyclical changes in temperature; the accelerating effects of vibration and temperature can be used for the calculations independently. However, [4] developed a model in which with equal flows of failure intensities during operation and testing, the mutual influence of factors leading to failures is taken into account. The model of the combined effect (acceleration of test modes causing failures similar to the operation ones) is the total acceleration factor (acceleration coefficient) [4]:

\[ F_{comb} = \frac{1}{N_F} \sum_{i=1}^{N_F} F_i \cdot \prod_k F_k \]

\[ \prod_k F_k \] – is a product of acceleration factors affecting the failure mode of the product; \( F_i \)- the acceleration coefficient for each of the forced factor.

The effective method for describing models of mutually influencing factors in models of forced equivalent cyclic tests is the physico-statistical method, according to which the test object is a thermodynamically unstable system that changes due to the global principle of entropy growth. To develop models of forced equivalent cyclic tests, a generalized mathematical model of resource consumption is used. It is developed by combining resource consumption models for individual elements of on-board electronic equipment depending on mutually affecting factors (for example, broadband random vibration and cyclic temperature change), reflecting only reliable physicochemical properties and mechanical processes.

For each stage of testing, the acceleration coefficient is calculated according to the expressions for BRV (8), for cyclic temperature changes during transportation:

1) 1) For the broadband random vibration:

\[ F_{Vibration} = \frac{\sqrt{G_{expl\ max_i}}}{\sqrt{(G_{xx} + G_{yy} + G_{zz})^b}} \]

2) For cyclic temperature changes during transportation:

\[ F_{Transp} = \left( \frac{\Delta T_{HALT}}{\Delta T_{oscillations_{transp}}} \right)^{-k} \times \left( \frac{V_{\Delta T_{HALT}}}{V_{\Delta T_{oscillations}}} \right)^{1/3} \]

3) For cyclic temperature changes during operation:

\[ F_{Exp} = \left( \frac{\Delta T_{HALT}}{\Delta T_{oscillations_{transp}}} \right)^{-k} \times \left( \frac{V_{\Delta T_{HALT}}}{V_{\Delta T_{oscillations}}} \right)^{1/3} \]

4) For cyclical changes in temperature during storage:

\[ F_{ST} = \left( \frac{\Delta T_{HALT}}{\Delta T_{oscillations_{transp}}} \right)^{-k} \times \left( \frac{V_{\Delta T_{HALT}}}{V_{\Delta T_{oscillations_{transp}}}} \right)^{1/3} + \frac{\left( \frac{\Delta T_{HALT}}{\Delta T_{oscillations_{transp}}} \right)^{-k} \times \left( \frac{V_{\Delta T_{HALT}}}{V_{\Delta T_{oscillations_{transp}}}} \right)^{1/3}}{2} \]

The model of the combined broadband random vibration and cyclic temperature changes for the equivalent cyclic test program is as follows:
\[ \Phi_{comb} = \left[ \frac{\Phi_{Vibration} \cdot \Phi^{\text{transp}}}{2} \right]_{\text{transp}} + \left[ \frac{\Phi_{Vibration} \cdot \Phi^{\text{test}}}{2} \right]_{\text{storage}} + \left[ \frac{\Phi_{Vibration} \cdot \Phi^{\text{expl}}}{2} \right]_{\text{expl}} \]

The combined ECT model at three stages of the product life cycle is as follows:

\[
\Phi_{comb} = 0.0833 \cdot \left( \frac{\Delta T^{\text{HALT}}}{\Delta T^{\text{osillations}}} \right)^{-k} \times \left( \frac{V^{\text{HALT}}}{V^{\text{osillations}}} \right)^{\frac{1}{3}} + \sum_{i=1}^{N} T^{\text{expl}} \left( \frac{G_{\text{expl \, max}}}{(G_{xx} + G_{yy} + G_{zz})^{b}} \right) + \left[ \left( \frac{\Delta T^{\text{HALT}}}{\Delta T^{\text{osillations}}} \right)^{-k} \left( \frac{V^{\text{HALT}}}{V^{\text{osillations}}} \right)^{\frac{1}{3}} \times \left( \frac{V^{\text{HALT}}}{V^{\text{osillations}}} \right)^{\frac{1}{3}} \right]^{1/3} \]

Parameter \( F_{comb} \) is the the acceleration coefficient of the MECTM.

6. Conclusion

The developed MECT model has the following advantages:

1) The multi-axis SHS has a synergistic effect creating test conditions equivalent to the real exploring modes;
2) The vibrational energy is focused in the high-frequency spectrum;
3) The acceleration factor (acceleration coefficient) is higher due to the refined calculation of the product of the WWF, in comparison with the tests conducted according to the sequential scheme adopted in the current regulatory and technical documents.

However, the negative effects of the MECTM are inherent in the HALT: failure mechanisms associated with wear may be absent due to too high acceleration factors. HALT procedures do not provide an adequate assessment of reliability for electromechanical products [9].

References

[1] Komissarov A V., Shishkin V V. 2018 The main methods for assessing reliability of on-board electronic equipment of modern civilian planes before the mass production. Bulletin of Samara Scientific Center of the Russian Academy of Sciences. 20, 4 (3) 319 - 326.
[2] Komissarov A V, Vinogradov A B 2016 Quality management methodology for on-board aircraft and ground equipment. Bulletin of Samara Scientific Center of the Russian Academy of Sciences. 18, 4 (3) 571 - 577.
[3] Olt J, Maksarov V V, Efimov A E 2018 Impacts of gradient structure on the dynamic characteristics of machining process system 29th Daaam international symposium on intelligent manufacturing and automation 190-196 DOI: 10.2507/29th.daaam.proceedings.027.
[4] Guru P P, Pecht M A 2018 critique of reliability prediction techniques for avionics applications. Chinese Journal of Aeronautics 31(1) 10–20.
[5] Maksarov V V, Keksin A I 2018 Technology of magnetic-abrasive finishing of geometrically-complex products, IOP Conference Series: Materials Science and Engineering, 327.
[6] Harry McLean, Mike Silverman, 2010, From HALT Results to an Accurate Field MTBF Estimate. Reliability Society 2010 Annual Technical Report.
[7] Maksarov V V, Krasnyy V A, Viushin R V 2018 Simulation of dynamic processes when machining transition surfaces of stepped shafts, IOP Conference Series: Materials Science and Engineering 327.
[8] Efimov A E, Maksarov V V, Timofeev D V 2017 Modeling dynamic processes at stage of formation of parts previously subjected to high-energy laser effects, IOP Conference Series: Materials Science and Engineering 327.
[9] Alekseeva L B, Maksarov V V 2018 Evaluation of effect of oil film of rotor bearing, IOP Conference Series: Materials Science and Engineering 327.
[10] Harry McLean, Mike Silverman 2010 From HALT Results to an Accurate Field MTBF Estimate. Reliability Society 2010 Annual Technical Report DOI 10.1109/RAMS.2010.5448013.