Low-Cycle Shock Fatigue of Electronic Components
Revision B

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Figure 1. Sony ICF-S10MK2 Radio

Introduction

There is a need to evaluate the reusability of avionics components subjected to repetitive flight shock environments with respect to qualification shock levels. As an example, this would be the case for a component recovered from one flight and then reused on another flight.

Qualification shock testing is typically performed on non-flight units to levels which are 6 dB greater than the maximum expected flight level. The 6 dB increase is double the flight level in terms of acceleration (G).

Fatigue scaling formulas are available for high-cycle random vibration, as given by Steinberg et al. A question is whether these formulas can be used to determine the number of flight shock lives demonstrated by each qualification shock.

Empirical data is needed to evaluate whether a fatigue life calculation can be made for shock.

Shock testing was performed on nine Sony transistor radios, as a simplified “pathfinder” test. Each radio was subjected to a series of free-fall drop shocks from a given height and tested to failure by monitoring the audio output.

The radio test results may be considered as anecdotal given that the orientation of the radio at impact was uncontrolled, and also given that accelerometer measurements were not made.

Nevertheless, a fatigue-type relationship was observed similar to that given by Steinberg in *Vibration Analysis for Electronic Equipment,* but with the radio test yielding a higher exponent.

Challenges

Avionics components are to some extent black boxes for mechanical engineering purposes. Here are some challenges:

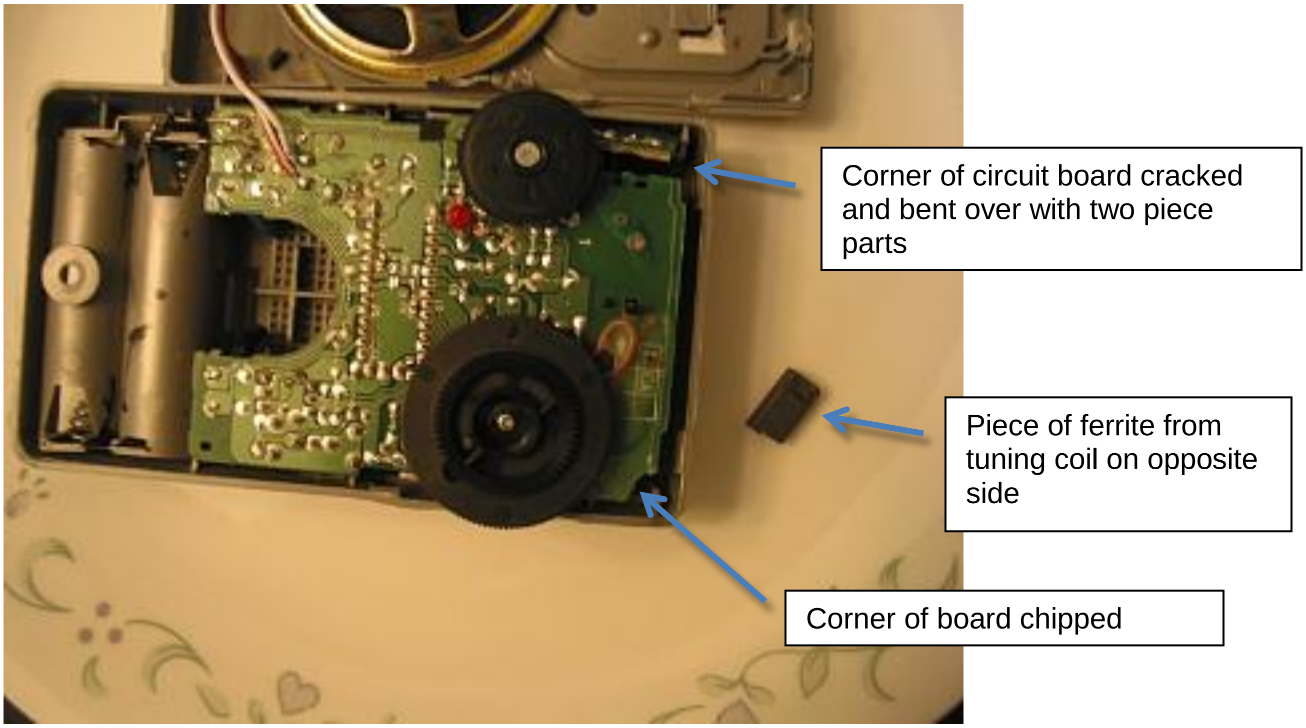
1. The component and its piece parts contain numerous materials, some of which are unknown.
2. The stress-strain curves for many of the materials are unknown.
3. Whether the materials are brittle or ductile is largely unknown.
4. The stress concentration factors are unknown.
5. The SN curves are unknown.
6. Even if the SN curves were known, SN curves seldom extend to the low-cycle fatigue range below, say, 1000 cycles.
7. Materials in some cases can withstand higher dynamic loads than the static, or quasi-static, loads that would lead to plastic deformation or failure.

Now assume that a component contains all brittle materials. The component has withstood one-cycle of a shock test. It did not fail. Its "dynamic ultimate stress limit" was not exceeded.

Next the component is subjected to a series of shock pulses each with precisely identical time domain signatures and corresponding shock response spectrum (SRS) curves. After so many identical cycles, the component is hypothesized to fail due to accumulated fatigue damage from microcracks, dislocation, fretting, etc. Thus repetitive shock can be treated in terms of accumulated fatigue, even though this may be low-cycle fatigue.

A substantial question remains as to what the fatigue exponent should be. The fatigue exponent from 1 to 10 cycles may be significantly different from that from 1000 to 1 million cycles depending on the material.

Test Description



Corner of circuit board cracked and bent over with two piece parts

Piece of ferrite from tuning coil on opposite side

Corner of board chipped

Figure 2. Failed Radio Circuit Board

Nine radios were assigned to a drop height. Some were assigned to the same height. Masking tape was applied to the outside of each radio to prevent the batteries from dislodging and to prevent the case from splitting open.

Each radio was dropped by hand from its height onto a concrete floor.

The radios were oriented so that the front side with the dial indicator was facing downward. The goal was that each radio would have zero initial velocity upon release.

Many of the drops met the goal of zero rotation, with each radio’s front side flatly striking the floor. But the radios underwent inadvertent rotation during for some of the drops.

Each radio had six sides, eight edges and eight corners. The initial contact between the radio and the floor varied among these 22 permutations. These permutations could be subdivided into further permutations given the angles involved.

Impact consistency was thus challenging. These effects tended to “average out” for the cases of lower drop heights where the radios underwent higher number of drops prior to failure. But the inconsistency caused some data scatter for the higher distances where failure occurred at less than 40 drops.

The variation in the quality of parts and workmanship among the radios may have had a secondary effect upon the scatter.

Failure Criterion

The radios were powered and monitored during each drop. The impact tended to jar the tuning so that the radio needed to be returned after many of the drops. This was allowed.

The failure criterion was that the radio would “go dead.”

This criterion proved to be challenging, because the performance of the radios tended to diminish gradually over successive drops. The signal-to-noise ratio decreased, and the radios were able to receive fewer stations.

Eventually, a corner of the circuit board[1] with two piece parts broke off as shown in Figure 2. This was the common failure mode in each radio. In addition, the ferrite inductor core fractured in some of the radios.

The failure criterion became that the radio could no longer receive any AM stations and that one or more broken parts were rattling around inside the radio housing.

The test results are shown in Table 1 and Figure 3.

Acceleration Level

Idealized assumptions can be made to calculate the circuit board response acceleration per Reference 1. Two variables are required: the impact velocity and the circuit board natural frequency. The impact velocity is easily calculated from the change in potential energy.

The circuit board natural frequency is unknown, however. Assume that it was in the domain from 300 to 600 Hz based on experience with other circuit boards. Note that a higher frequency yields a higher G level. The maximum drop height was 76 inches. The resulting acceleration would have been from 1183 G to 2366 G.

The impacts were rather violent.

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[1] Circuit boards are commonly made from G10 which is a fiberglass/epoxy material. which tends to be brittle in compression but ductile in tension.

Test Results

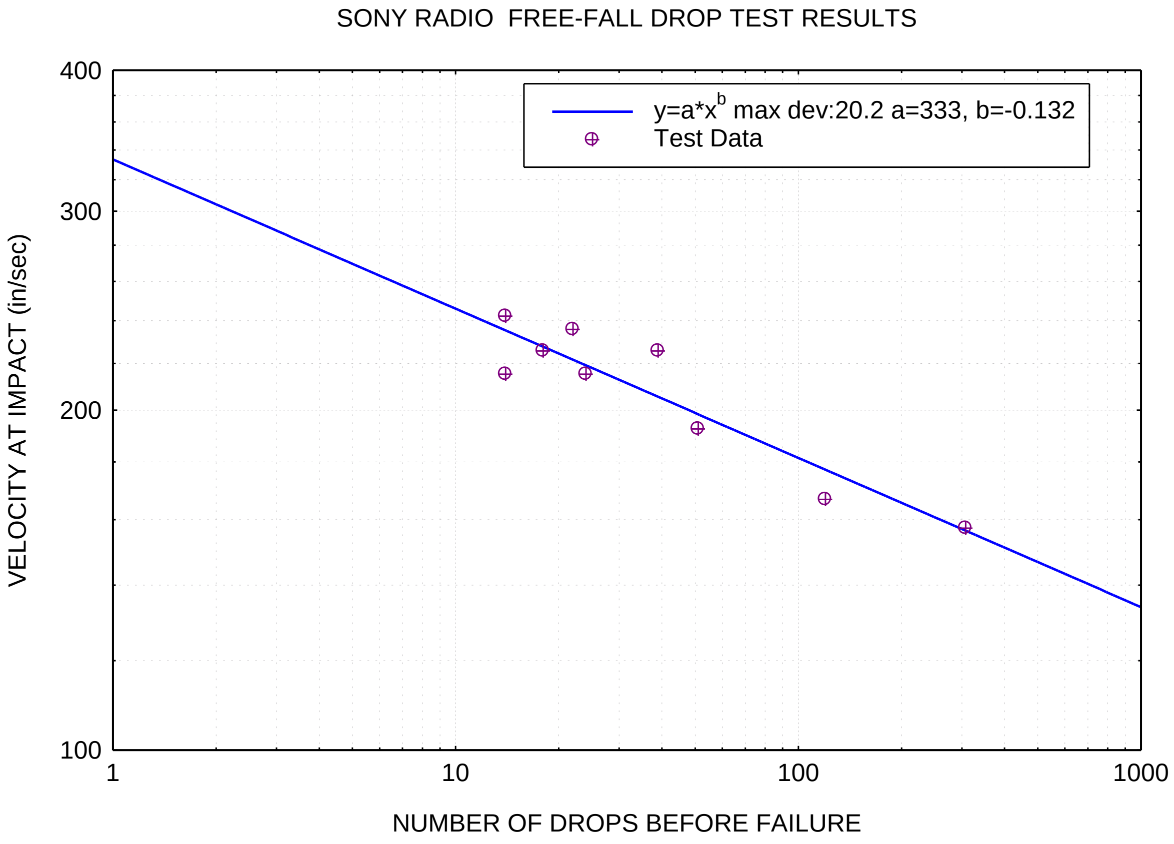

Figure 3.

Table 1. Tests Results for Nine Radios		
Drop Height (inch)	Velocity at Impact (in/sec)	Drops Before Failure
76	242.2	14
72	235.8	22
66	225.7	18 & 39
60	215.2	14 & 24
48	192.5	51
36	166.7	120
32	157.2	308

Scaling Equation

The following equation is taken from Steinberg, Reference 2, section 8.25, page 238.

$$T_1 G_1^b = T_2 G_2^b \tag{1}$$

where each G value is in terms of GRMS.

Furthermore, the exponent b is taken as 6.4 for PCB-component lead wires. This number is derived in Reference 2, section 7.3, page 177. It represents generic metal. It is used in Reference 2 for both sine and random vibration.

MIL-STD-1540C gives a similar equation for random vibration but with an exponent of 4.

The exponent from the radio test is taken from the graph in Figure 3 as

$$1 / 0.132 = 7.6$$

A comparison of these methods is given in Table 2.

Table 2. Fatigue Formula Comparison, Equivalent Flight Lives

Qualification Margin above Maximum Flight Level	MIL-STD-1540C	Steinberg	Radio Test
3 dB	4	9	14
6 dB	16	84	191

Further margin is desired given the nonlinearity of shock response and other factors. The number of lives should be taken as one-half of those in Table 2 for application to a given component, per Reference 4.

Conclusion

The free-fall test of the Sony radios was intended as a “pathfinder” to guide further, more rigorous testing.

But the test successfully demonstrated that a fatigue relationship can be applied to low-cycle shock.

An accurate estimate of the fatigue exponent remains a challenge, as it has always been.

The fatigue exponent can be expected to vary by component, depending on materials, geometry, stress concentration factors, etc.

References

1. T. Irvine, Simple Drop Shock, Rev D, 2004.

2. Dave Steinberg, Vibration Analysis for Electronic Equipment, Second Edition, Wiley-Interscience, New York, 1988.

3. MIL-STD-1540C, Military Standard: Test Requirements for Launch, Upper-Stage, and Space Vehicles (15 SEP 1994).

4. T. Irvine, Qualification Shock Testing for Reusable Avionics Components, 2011.

APPENDIX A

Low-cycle fatigue from aftershocks is a concern in earthquake engineering.

Jun Iyama and James Ricles wrote:

> A building may suffer damage during an earthquake as a result of inelastic deformations developed in the members or connections. It is important that the structural integrity of the building be assessed to ensure the safety of the occupants. This assessment includes evaluating the ability of the structure to resist the demand from subsequent aftershocks and a major earthquake.

Reference: Prediction of Fatigue Life of Welded Beam-to-Column Connections under Earthquake Loading, J. Struct. Eng. 135, 1472 (2009).