Investigation of Failure Mechanisms of Low Power Isolators and Circulators

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INTRODUCTION

Ferrite devices are key hardware in satellite payloads but their reliability aspects are not well documented and especially, there is no evaluation or qualification data available in the ESCC system. This paper presents an ESA funded TRP project which objective is to identify and validate the failure and fatigue mechanisms of low power ferrite devices such as circulators and isolators and to assess experimentally the maximum allowable stress levels and so the data necessary for the ESCC specifications (e.g. for derating, screening and qualification). An analysis of the specific materials, assembly parameters, RF performances and applicable requirements of these passive RF devices is presented, as well as a review of the relevant physics of failure and their acceleration models. Finite Element Analysis as well as acceleration and fatigue life prediction models are used to predict the maximum stress testing levels (temperature, vibration, shock and RF power) and the maximum number of cycles for fatigue. An Evaluation Test Plan based on ESCC requirements is defined and implemented on test units in order to verify these failure predictions. Preliminary results are only presented here and the results of the complete Evaluation Test Plan will be presented during the Symposium.

FERRITE CIRCULATORS AND ISOLATORS

Circulators are non-reciprocal 3-port passive devices using the magnetic properties of ferrites, and widely used in transmit / receive systems to direct signals according to their origin. They are more efficient than electronic or electro mechanic switches at high frequency, more robust, lower cost and do not require external circuit to operate. They have an additional advantage to provide isolation as needed. A Y-junction combined with a ferrite disk polarized with a magnet creates a gyromagnetic effect which allows a wave entering in any of the three ports to exit only in the next adjacent port, clockwise or anticlockwise depending on the field direction. Such a device is principally used as CIRCULATOR for directing the RF signal everywhere the separation between Tx and Rx channels is important (radars, satellite links, mobile com …) or as ISOLATOR for inter-stage isolation to mask a mismatch between subsequent elements in a transmit chain, or to protect against poor VSWR or any short circuit. This ISOLATOR function is obtained when one of the ports is isolated by a matched load.

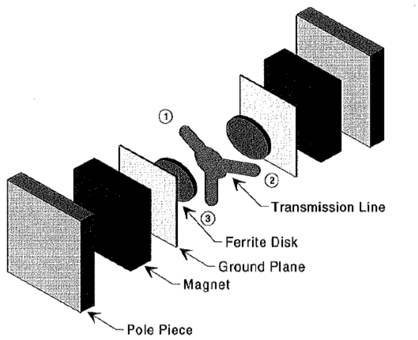

Fig. 1. Stripline circulator construction

Depending on equipment requirements, frequency, signal power level, different technologies and different input/output access types are available. A strip-line construction is shown expanded in Fig. 1. Two different strip-line technologies, coaxial and drop-in, relevant to this investigation, are presented below (isolators, with resistive load on port 3) . In the frame of this investigation, all the constitutive materials, their thermo-mechanical properties and their assembly parameters have been described in details for the Finite Element Analysis.

Fig. 2. Coaxial isolator

Fig. 3. Drop-In isolator

FERRITE DEVICE RELIABILITY AND FAILURE ANALYSIS

Isolators and circulators are very reliable devices but there is no data in the literature dealing with failure mechanisms, and very few relevant reliability data [1].

Handbooks or methods such as MIL-HDBK-217 or FIDES [2], based on the empirical approach (collection of reliability data from the field, base failure rate modified by several π factors covering configuration, environmental and quality aspects) provide some reliability data for ferrite devices but their relevance is questioned [3] and space industry customers usually have their own reliability figures (FITs) for these specific devices.

The analytical approach is based on a physics of failure methodology (identification of failure mechanisms, performance of accelerated stress tests, identification and modeling of the dominant failure mechanism, combination of test data with statistical distributions, development of equations for dominant failure mechanism and MTTF) [1, 4].

As a first step of this investigation, the table below summarizes the anticipated failure modes and mechanisms for ferrite devices subjected to stress types and levels relevant for space applications, as well as stress tests and methods for their investigation.

Table 1. Failure mechanisms of ferrite isolators

Type of stress	Failure mode	Failure mechanism	Failure detection test	Failure analysis
High temperature	Parameter drift Open circuit Crack or break	Material degradation. Solder melt. Overstress (heat or thermomechanical)	Temperature step stress test	Electrical testing Visual inspection DPA
Thermal cycling	Parameter drift Open circuit Crack or break	Thermal mismatch. Stress relaxation Fatigue	Thermal cycling with extended temperature range, Extended number of cycles	Electrical testing Visual inspection DPA
Vibration	Parameter drift Open circuit Crack or break	Material/bonding ruptures or cracks. Deformation. Loosening of parts Fatigue (unlikely)	Vibration step stress test (acceleration levels). Extended duration (not applicable for space)	Sine survey Electrical testing Visual inspection DPA
Mechanical shock	Parameter drift Open circuit Crack or break	Material/bonding ruptures or cracks. Deformation	Shock step stress test (acceleration levels)	Electrical testing Visual inspection DPA
RF Power	Parameter drift Open or short circuit	Heating effects Load burn-out	Power step stress	Electrical testing Visual inspection DPA

Maximum allowable levels shall be determined for each type of stress in order to specify derating factors, screening and qualification levels for the ESCC specifications. In this activity, these maximum allowable levels have been first determined by analysis and then assessed experimentally by actual stressing several units for each stress type and step by step. A drop-in structure has been selected for this investigation.

MECHANICAL ANALYSIS OF A DROP-IN ISOLATOR

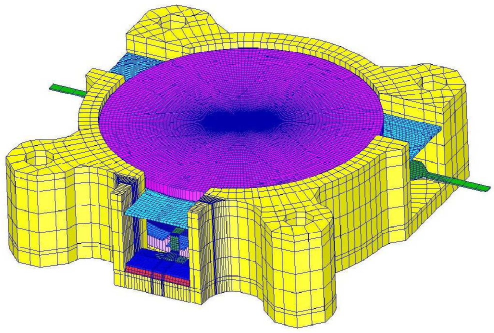

Fig. 4. Finite Element Model of the Isolator structure under investigation

Finite Element Modeling of a Cobham drop-in isolator (ND1165-122), performed by MecanoID with MSC Nastran Software, has allowed to compute the stresses generated by the assembly (pre-load) and by the different environmental specifications relevant to space applications. Random vibration, shock and thermal cycling specifications for Qualification level of ESCC 3202 (Generic Specification for Ferrite Isolators and Circulators) have been used as base line.

The modal analysis shows that there is no structural mode below 1000 Hz. All margins with respect to qualification levels are found positive and for each environment, the maximum allowable levels (i.e. leading to permanent deformation or rupture) have been computed. These levels are shown in Table 2 below.

Both for shock and vibration, the limiting elements are the ferrite and the magnet. The different values shown in Table 2 correspond to different assumptions on the safety margins used for the analysis.

For thermal cycling, the classical thermo elastic analysis does not take into account the elastic-viscoplastic behavior of solders (creep phenomena) and leads to negative margins. In order to have a more realistic analysis, a thermo mechanical model described in the literature for electronic solder joints, has been adapted and analytically solved [5-6]. It has allowed the simulation of the behavior of the two solder joints under imposed temperature cycling by generating the stress/strain hysteresis loops and has confirmed that the maximum thermo-mechanical stresses are allowable and not critical.

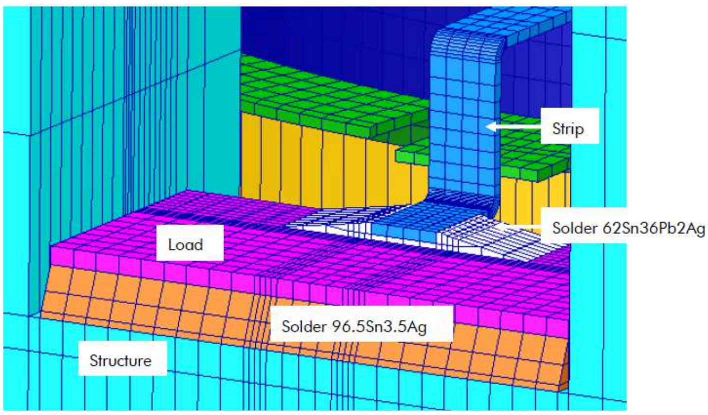

Fig. 5. Zoom on the solder area (chip load to housing and strip to load assembly)

Further to this result, this analysis has allowed to estimate the thermal fatigue life of the solders by using classical acceleration model (modified Coffin Manson law [7])

EVALUATION TEST PLAN

The Evaluation Test Plan philosophy is based on the ESCC detail Specification No. 2263202 (Evaluation Test Programme for Ferrite Microwave Components). The aim is to overstress the specific characteristics of the components with a view of detection of possible failure modes and to assess the maximum allowable levels predicted by the simulation analyses. Obviously some levels can be difficult to reach due to equipment availability or physical limits, especially for such robust devices.

The following table summarizes the maximum allowable levels obtained by these analyses. These levels are compared to the ESCC 3202 qualification levels. In order to assess these levels and to implement the Evaluation Test Plan, maximum achievable levels are proposed in this table, with their justification.

Table 2. Stress Levels

Type of stress	Qualification level from ESCC 3202	Max allowable level from analysis	Max evaluation level for ETP	Justification
High temperature	80°C max operating 85°C max storage	NA	180°C	Temperature limit of solder
Thermal cycling	-40°C/+85°C Storage extremes 200 cycles	-55°C/+125°C > 30 000 cycles	-55°C/+125°C 500 cycles	Validity range of the models (Coffin-Manson)
Vibration	50 gRMS overall 10-50Hz +3dB/Octave 50-1000Hz 1,5 g²/hz 1000-2000Hz -3dB/Octave duration 180 s x 3 axes	97 to 128 gRMS	120-130 gRMS 180s x 3 axes (3)	Equipment availability
Mechanical shock	Half sine 1500 g 0,3 ms N= 18 (3 x 2 directions x 3axis)	3100 to 4080 g	4000 g	Equipment availability
RF Power	At center frequency Max rating of isolator 10W-CW forward power 5W-CW reverse power	NA	15W reverse power	Max power handling of load. Self heating to solder limit.

The Evaluation test sequences are described in the figure below. Step stress tests are performed for each stress type, up to the maximum achievable level. The step stress sequence shall be terminated when 50% of the specimens have failed. All failed components shall be analysed in order to determine the failure mode.

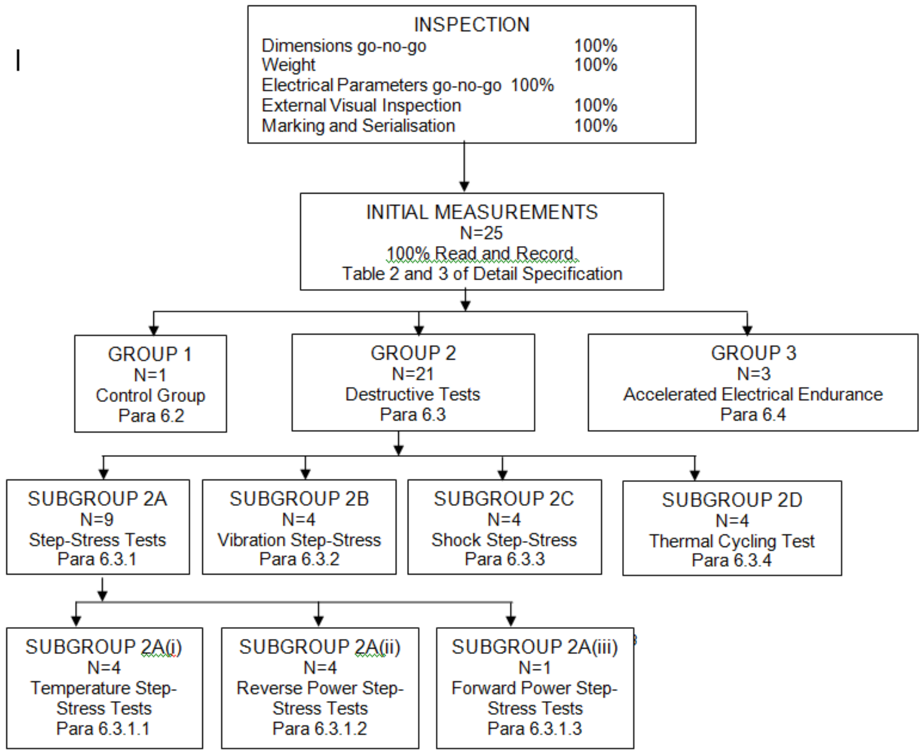

Fig. 6. Evaluation Test Plan

The detailed result of this Evaluation Test Plan will be presented during the conference.

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