Vibration Induced Harness Failure Investigation

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ABSTRACT

A wiring harness in an aircraft engine, and in aircraft systems, has the vital function of conveying sensor information and carrying power to various components. Some harnesses, especially in the vicinity of a broad-spectrum high vibration and high temperature environment, can experience unexpected internal damage and cause faulty readings. This can happen despite following the best industry practices developed for such wire harnesses. A series of investigations have been conducted at the Raytheon Technologies Research Center (RTRC) Structural Dynamics Laboratory to understand the underlying reason for the vibration induced harness failures. When subject to the operational vibration spectrum, we were able to capture the first two bending modes of the suspect harness with a high-speed camera. From the mode shapes, we can extract the harness bending distribution. In addition, the temperature distribution of the harness resonating at its modal frequencies is measured with an infrared camera, and several hot spots are identified. These hot spots coincide with the locations with highest bend locations. The accelerated endurance test was then conducted, in which the harness is excited at the mode of interest. The resistance of the harness shield is monitored in real time to assess the damage severity. Towards the end of the endurance test, the resistance increases exponentially. The tear down confirmed that the failure mechanism is the wire fretting induced by the first harness bending mode. The evaluation procedure of the fretting risk is described, and the mitigation method is proposed at the end.

1. BACKGROUND

The wiring systems of modern aircraft are subject to a host of unusual operating environments. Further, each aircraft may have tens to hundreds of miles a wire and thousands of connectors supporting electrical system components. As aircraft age, the components age and they become more susceptible to wiring failures. In 2017, Lectromec published a white paper on failures of electrical wiring interconnection system (EWIS) on commercial aircraft [1]. The report states that aircraft older than 20 years, are twice as likely to have EWIS failures compared to those in the 10~15-year bracket, based on thousands of service reports filed with the FAA.

The analysis of the EWIS harness and connector has been widely studied in [2~6]. Many studies focus on the aging of the insulation, the failure of the interconnector, the fretting of the connector contacts. There are several natural causes for EWIS degradation in aircraft, i.e., vibration, moisture, heat. The harnesses subject to high vibration tend to accelerate degradation over time, resulting in "chattering" contacts and intermittent symptoms. High vibration can also cause tie wraps, or string-ties to damage insulation. In addition, high vibration will exacerbate any existing problem with wire insulation cracking.

A typical EWIS wire harness is shown in Figure 1, which has a tree-like structure. There are many branches connecting to sensors, and they merge to form the main bundles. The main bundles are very thick and usually are mounted to the rigid engine frame, which experiences less vibration. The branch wires are thin, and between the connected sensor and the main bundle, the branch wire is supported intermittently with clips. Those clips may sit on pipes or brackets, which are less rigid than the air frame and are subject to higher vibration in general. The harness branch from the sensor to the first clip usually has a relatively long span. Therefore, the first couple of bending modes of that segment of the harness are in the low frequency range.

Figure 1. Typical Aircraft EWIS

With increasing size and power of engines in the modern aircraft, the vibration tends to become more severe. Especially during taxing, landing and taking-off, where more vibration is seen in the low frequency range. Therefore, in this regime, the risk of the vibration induced harness failure is accentuated. One rare but severe harness failure mode is the harness internal wire break.

In this paper, the mechanism of the harness failure is analyzed and verified experimentally. This is followed by an accelerated failure test to confirm the suspect failure mode.

2. FAILURE ROOT CAUSE ANALYSIS

The harness assembly consists of several layers: the wires, the internal sheath, the armature (metallic braid shielding) and the external sheath. The generic harness cross-section layout is illustrated in Figure 2.

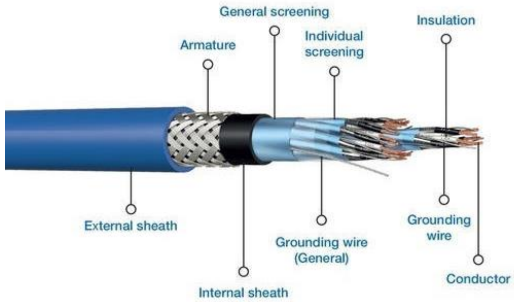

Figure 2. Typical harness construction

When subject to vibration, the harness deflects and bends. The harness bending can cause sliding between the sub-components, such as wire to wire and layer to layer. The amount of the sliding depends on the bending magnitude and the distance from the neutral axis of the harness. The relative sliding between component has two major impacts. One is the local heat generation created by the contact friction, which can heat up the component. The heat can cause the oxidation of metal, which is apparent as discoloration. The other impact is material abrasion or fretting, which usually results in observable debris. Overtime, the wire insulation can be worn resulting in a short circuit and/or the wires in the metallic braid shielding can be broken.

Usually, the material of the wire insulation is made of TEFLON, which has a very low coefficient of friction to reduce the risk of the contact heat generation. However, the metallic braid shielding can experience relatively higher sliding in certain location, and the metal-to-metal contact has a relatively high friction. Thus, the braid shielding has a higher risk of fretting. This fretting can be worsened if the harness vibrates at its resonance.

Once the wire in the shielding breaks, the sharp tips can penetrate and damage the internal insulation to cause the intermittent short circuit, which results in the erroneous signal.

3. FAILURE MECHANISM VALIDATION TEST

To verify that vibration was inducing the fretting mechanism within the harness, a series of tests were conducted at RTRC.

To mimic the operational environment the harness is mounted in its actual geometric layout. The connector side of the harness is connected to the sensor and the harness is clamped on a fixed frame with a butterfly clip. The span of the harness is approximately 8 inches. The sensor is mounted on a fixture made of non-conductive composite material; and the fixture is mounted on the shaker head. The purpose of the non-conductive fixture is to insulate the harness from the shaker, such that the resistance measurements can be recorded during test.

The first step of the investigation is to identify the vibration modes of the harness through the sine-sweep test. The frequency sweep range is set from 30Hz to 400Hz with a sweep rate at 2.5Hz per second. The excitation levels are 5G, 10G and 15G. The harness, due to its multi-material and layered structure, has a strong nonlinear behavior, therefore the resonance frequency may shift with the vibration level. The vibration of the harness is measured directly with a laser vibrometer. An accelerometer is mounted on the back shell of the connector, which captures the actual boundary excitation to the harness. The test setup is shown in Figure 3.

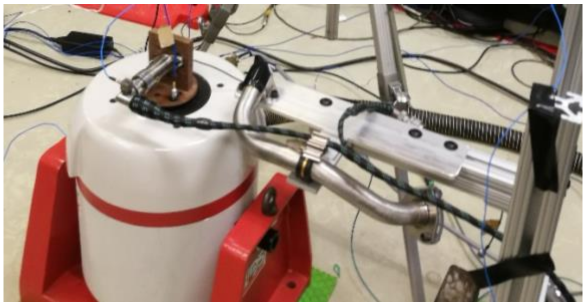

Figure 3. Harness vibration testing setup

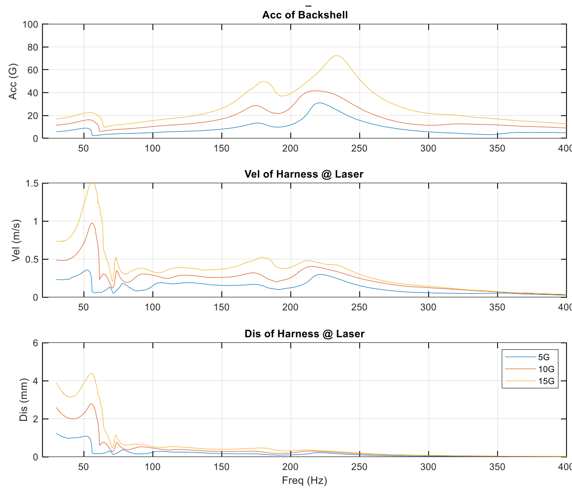

Figure 4. FRF of harness

One Frequency Response Function (FRF) of the harness is plotted in Figure 4. The harness has a dominant resonance frequency at around 53 Hz measured by the laser vibrometer. At the back shell, there is another noticeable mode at around 220Hz, which cannot be clearly seen in the harness. This indicates that 220Hz is associated with the sensor and mounting structure. In the following test, both modes are explored. The above two modes can vary slightly from harness to harness. In the accelerated failure test, each harness is excited as its own modes.

To confirm the internal fretting mechanism, the correlation between the harness bending and the temperature rise is investigated with the sine dwell test, in which the harness is excited at those two modes respectively. The harness vibration is captured by a high-speed camera, then the video images are processed to extract the harness deflection shape. The bending distribution is computed from the deflection shape by numerical differentiation. Then the maximum bending variation along the harness is calculated over 50 cycles, which is defined as the bending magnitude. During the sine dwell test, the steady-state harness temperature distribution is also captured by an infrared camera. The high-speed camera and infrared camera setup are shown in Figure 5.

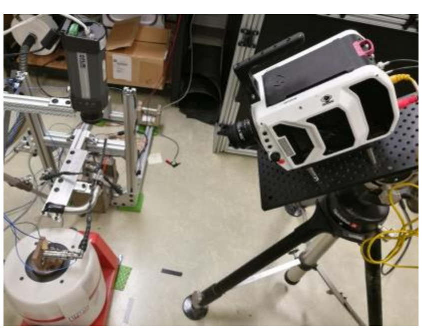

Figure 5. High-speed camera and Infrared camera Setup

A frame of the vibratory shape extracted from the high-speed video is shown in Figure 6. The left figure is the actual harness shape, the right figure is the deflection shape with respect to the stationary harness position.

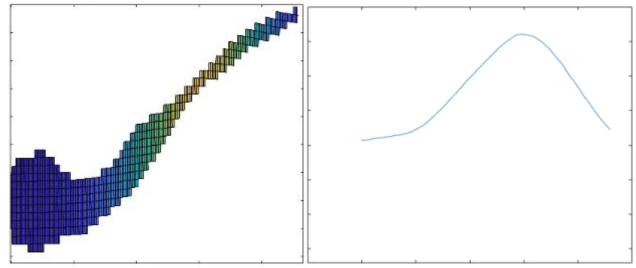

Figure 6. Harness deflection shape

The calculated bending magnitude and the corresponding thermal image at two modes – 53Hz and 228Hz – are shown in Figure 7 (a) and (b), respectively. It is very clear that there is a strong correlation between the high bending magnitude and the temperature rise at specific corresponding spots, which confirms the occurrence of the internal fretting, and temperature rise resulting from the vibration.

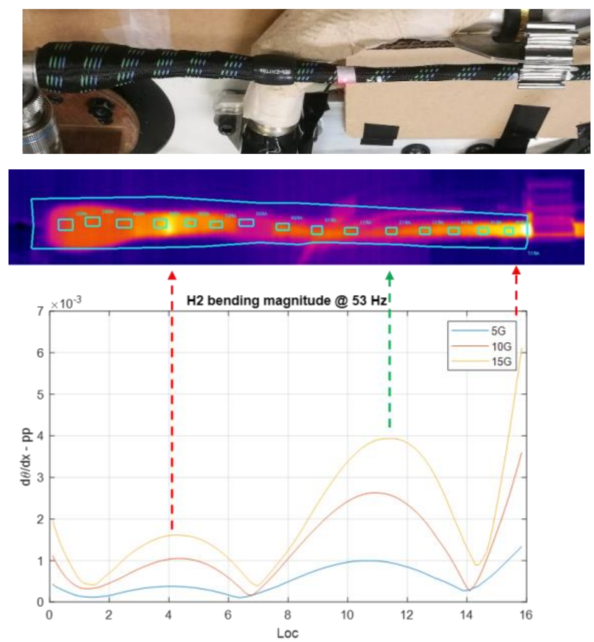

Figure 7(a). Thermal image and bending magnitude at 53Hz

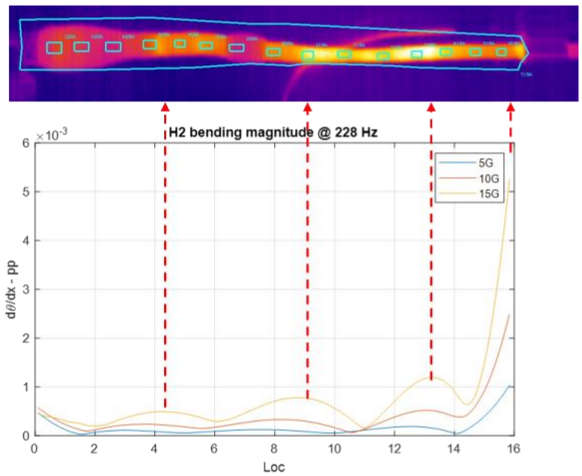

Figure 7(b). Thermal image and bending magnitude at 228Hz

At 53 Hz, there are three locations with high bending magnitude – Loc 4, 10, and 15. Loc 4 is at the end of the taper joint from the connector to the harness wire, and Loc 15 is at the clamp location. Due to the internal structure, the bending stiffness at Loc 4 is relatively low compared to the adjacent harness, so called kink spot. In the thermal image, there are two hot spots – Loc 4 and 15, and Loc 10 is relatively cool. The temperature rise is affected by three factors: sliding speed, and contact pressure. The sliding speed is determined by the bending magnitude, the frequency and the distance from the sliding layer to the neutral axis /diameter of the harness. At Loc 10 and 15, the diameter is identical, Loc 15 shows a higher temperature due to the higher local bending magnitude. At Loc 4, the bending magnitude is lower than Loc 10 and 15, while the sliding speed and contact pressure are relatively high due to its larger diameter, therefore the temperature is high.

At 228 Hz, there are four high bending areas, each area coincides with a hot spot. The bending magnitude is lower than that at 53Hz in general, however the temperature rise is still high, which can be seen later. It is driven by a higher sliding velocity, which is proportional to the frequency.

4. ACCELERATED FAILURE TEST

The accelerated failure test is conducted to validate the failure mode. The resistance of the entire shielding is measured as an indicator of the damage to the shielding. The wire break in the braid shielding leads to the increase of the electrical resistance. There are two resistance measurements: one is the dynamic resistance measurement with a Wheatstone Bridge, which can provide the real-time indication of the shielding integrity during test. The other is the static measurement with a high precision ohmmeter, which is done intermittently during the test break.

The harness temperature is recorded at fifteen evenly space spots along the harness. The temperature rise at those spots are defined as the difference between the measured temperature and the ambient temperature.

There are two test criterions. One is the shielding resistance increases by about 100~150%. The other is the number of cycles reaching 40 million. Once one of criteria is met, then the test is terminated.

H1 Test

The first harness H1 is tested at 57Hz, the excitation level is set at 15G. The time history of the temperature rise is shown in Figure 7. Loc 4 (kink location) and 15 (clamp location) show the highest temperature rise with respect to the room temperature, which can reach 13 F. The temperature dips are a result of the test breaks for the static resistance measurement. The temperature remains relatively stable over the entire test.

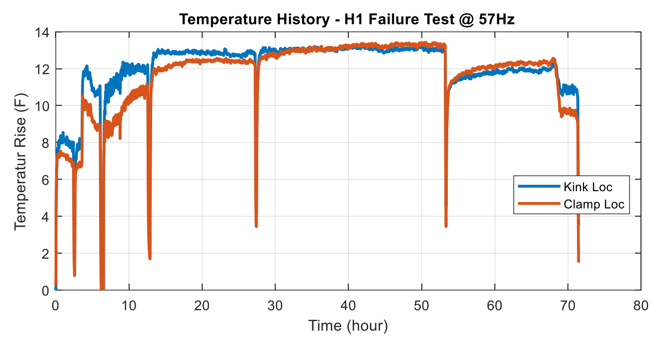

Figure 8. Temperature rise history of H1 failure test

The dynamic and static resistance measurement are shown in Figure 9(a) and (b), respectively. The dynamic resistance includes the resistance of the connection wires to the Wheatstone Bridge, so it is higher than the static value. The resistance is relative flat prior to 55 hours. After that it began to gradually increase. After 65 hours, the resistance reading begins to take off. At 72 hours, the dynamics resistance is very high and the static resistance readings confirms the actual resistance increased by 170%. The harness is claimed 'failed' and the test is stopped. The trend of the dynamic resistance shows good agreement with the typical mechanical system failure trend. Over the 72 hours test, it accumulated 15 M cycles.

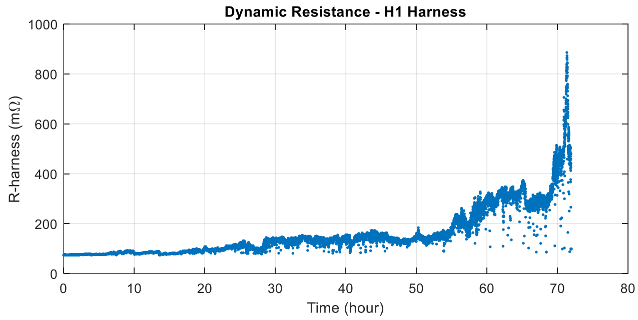

Figure 9 (a). Dynamic resistance history of H1 failure test

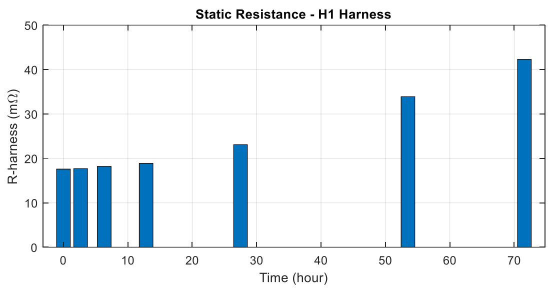

Figure 9 (b). Static resistance history of H1 failure test

H2 Test

The second harness H2 is tested at 53Hz, the excitation level is initially set at 15G as H1 test. After 64 hours, no resistance increase is observed. Then the excitation level is increased to 25G. The test lasted for another 48 hours until the static resistance increased by 140%. The time history of the temperature rise is shown in Figure10. At 15G excitation, the temperature rise at kink location is only 3 F, much lower than 13F in H1. The lower temperature indicates less friction induced heat and less fretting. Therefore, H2 does not show any sign of failure in the dynamic resistance at 50~60 hours like H1 did. When the excitation is increased to 25G, the temperature rise jumps up to 20~25F, and the harness fails in 48 hours. From H1 and H2 test, it clearly demonstrates that the temperature rise is a good indicator of the severity of the fretting.

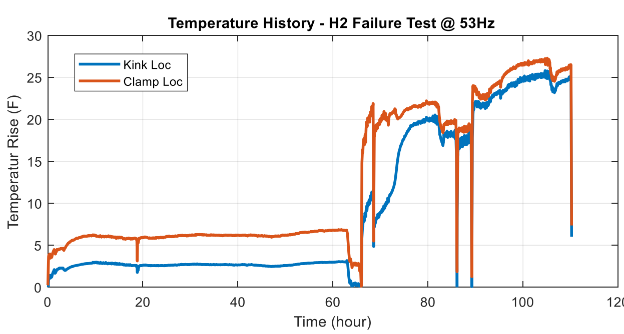

Figure 10. Temperature rise history of H2 failure test

The resistance measurement of H2 test is shown in Figure 11. The resistance maintains unchanged prior to 110 hours, after then it takes off with a sharp rise.

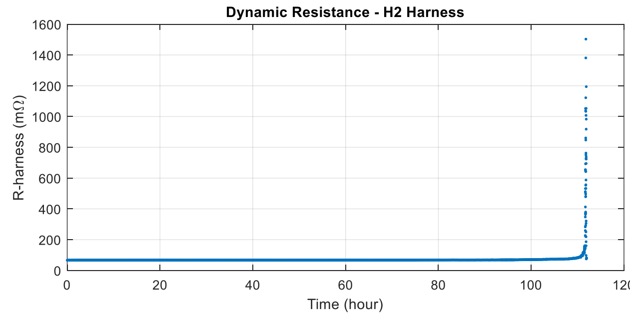

Figure 11(a) Dynamic resistance history of H2 failure test

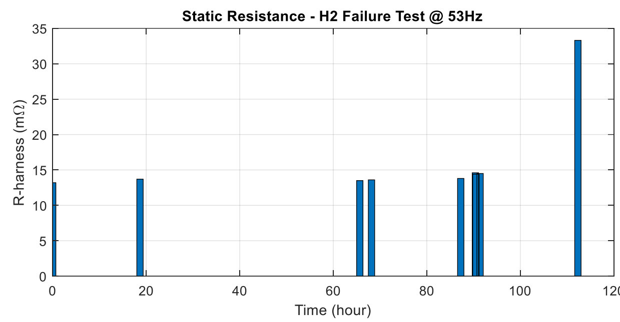

Figure 11(b) Static resistance history of H2 failure test

H3 Test

The third harness H3 is tested at 211Hz. The excitation level is set as 15G. The time history of the temperature rise of the harness with respect to the ambient temperature is shown in Figure 12. The harness H3 shows a temperature rise over 28F at Location 13, which is twice of H1 test. While the bending magnitude at 211 Hz is lower than that at 53Hz, as shown in Figure 7(b). The higher temperature is caused by a higher sliding speed due to a higher frequency.

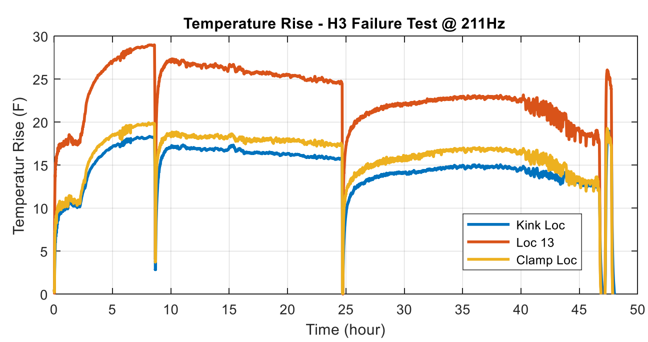

Figure 12. Temperature rise history of H3 failure test

The test lasted about 55 hours and accumulated over 40 million cycles in total. The dynamic and static resistance measurement are almost unchanged as shown in Figure 13.

Therefore, the test is stopped, and the harness is determined as no damage.

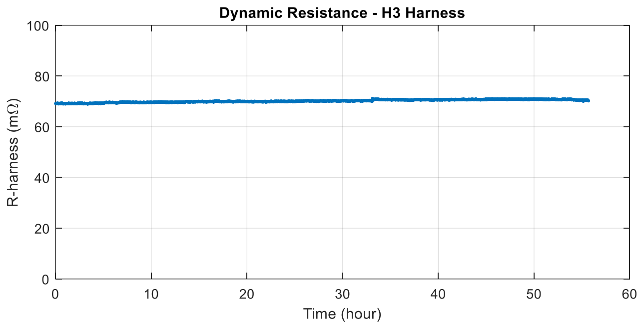

Figure 13(a) Dynamic resistance history of H3 failure test

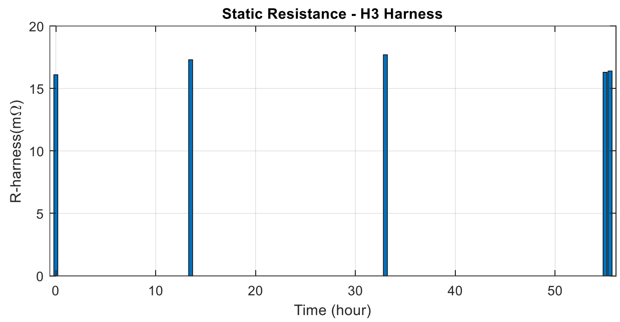

Figure 13(b) Static resistance history of H3 failure test

Although the temperature is a good indicator of the internal wire sliding, it can't be directly translated to the severity of the abrasion/fretting and the degradation rate. The wire contact pressure is the other important factor of the fretting, which is directly related to the bending magnitude and the harness diameter. Therefore, the temperature rise can only serve as the 'partial' indicator of the fretting. From this testing, it indicates that the bending mode at a higher frequency has very low impact on the fretting. Therefore, the first bending mode is of the most interest.

After the accelerated failure test, the harness H1 is CT scanned to inspect the braid shieling integrity, which reveals the wire break within the braid shielding. Finally, the harness is teardown, and the actual damage is confirmed, as shown in Figure 14. There is extensive wire break within the shielding, accompanied with the metal debris and discoloration, as expected.

Figure 14. Actual wire damage after teardown of H1

5. EVALUATION AND MITIGATION

The accelerated failure test confirms the failure mode, which is the wire abrasion and fretting in the metallic shielding induced by vibration. The harness segment from the sensor to its first clamp location is subject to a higher risk of failure, where the bending mode is in the low frequency range. Within this segment, the failure tends to occur at the end of the taper ramp/kink location, where the bending stiffness is lower than the adjacent section. The other important observation is that temperature rise is a good indicator of the wire sliding, but it can only serve as a 'partial' indicator of the abrasion/fretting. The contact pressure is another key factor, which has different level of impact on the heat generation and fretting/abrasion. The test indicates that the low frequency bending mode has the highest potential of causing failure.

Harnesses are manually assembled with some good standard practiced. To reduce failure risk of the harness and harness layout, a lab test can be conducted during the design process. The first step is to inspect the bending stiffness manually to identify any spot likely to form a "kink" band. If, when bent, the harness segment yields a smooth/gradual curvature, it indicates the absence of the kink spot, and the harness has a minimum risk. If a kink spot is present, then the harness should be subject to a validation test. The harness is setup per design layout, and the first bending mode is measured with a shaker test. If the first mode is in the low frequency range, i.e., <100Hz, then the harness may be subject to a high bending magnitude. If the first mode is high (i.e., >100Hz), the fretting risk is reduced significantly. The harness with a low bending mode should be further tested, in which the harness is excited at its first bending mode at 10~15G level. Then the steady-state temperature rise can be used to assess the fretting risk. If a high temperature rise is observed at the kink location, i.e., >10F, then it has a very high risk of failure.

Further, to mitigate the failure risk due to fretting, there are two general approaches. One is to improve the harness design to eliminate the "kink" spot. The other is to change the harness layout to suppress the vibration. For example, a simple solution is to reduce the harness span to increase the frequency of its first bending mode. A series of test have been conducted by varying the harness span and the effectiveness has been confirmed.

6. CONCLUSIONS AND DISCUSSION

The vibration induced harness failure was studied and described in this paper. The failure mechanism is identified as the wire abrasion within the metallic shielding braid. The abrasion is caused by the harness bending and results in the elevated temperature at the locations with the high bending magnitude, which is revealed by the vibration shape captured by the high-speed camera and the thermal image captured by the infrared camera. The segment of the harness from the sensor to its first clip location is more prone to this failure. In this segment, a “kink” spot with low bending stiffness usually appears at the end of the transition ramp. Due to its span and soft supports, its first bending mode is in the low frequency range, which can coincide with the engine order and resonate to yield a high vibration magnitude at the kink spot. The accelerated failure test confirms the failure mode. It also reveals that the bending magnitude is the major factor of the harness failure, and the correlation between the temperature rise and the severity of the abrasion. The testing procedure to identify and evaluate the failure risk is present. The mitigation approaches are also discussed in the paper.

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ACKNOWLEDGEMENT

BIOGRAPHIES

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Dr. Zaffir Chaudhry is a Research Fellow at RTRC specializing in mechanical systems design, vibrations, bearing tribology and diagnostics. Dr. Chaudhry has 25 years of engineering and R&D experience and has led many multidisciplinary projects to TRL6 and into product release. He holds a PhD in Mechanical Engineering from Virginia Tech where we were deeply involved with the foundational work on health monitoring of machines and structures. Dr. Chaudhry has 60 patents and is author of over 70 publications on actuation, sensing, health monitoring and mechanical systems.