The effect of thermostatic test environment on the flexural fatigue performance of hydraulic hose assemblies

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Abstract. The present study investigates the effect of thermostatic subzero (-65°F) and high ambient temperature (+275°F) on the hose performance when tested at a flexing frequency of 70 CPM with an amplitude of ±3.5 inches. The investigation was carried out through hose tear down analysis which includes surface and subsurface deformations at crimp zone, wire braid analysis, over the crimp silicon crack propagation, and microhardness measurements. It was observed that the flexing mechanism of hose when combined with thermostatic subzero and high ambient temperature, it contributes to different deformation mechanisms for the hose and the fitting juncture.

1. Introduction
A variety of specifications can be selected when certifying the hydraulic hoses from a simple proof set up to the most sophisticated test requirements. There are hose assemblies being used on the aircraft which demands for actuation or flexing in operation e.g. landing gear application and thrust reversal system. These hose assemblies’ needs to be qualified for the flexural fatigue performance to their specified number of flexing cycles. The hose flexibility test is more specifically defined to verify the flexural fatigue performance of wire braids and fitting attachments of hose. As the hose assembly experiences flexing motion, the effect of pressure level would be expected to show a typical fatigue stress curve on both the free length of hose and fitting attachments [1]. The high pressure hoses are widely used for the vehicles, aircraft, and overall industries. The performance of these high pressure hydraulic assemblies is not only limited to pressure needs but also includes extremes of temperature with a fairly high level of oil resistance at high volume flows, plus flexing at a very small bend radius in some instances [2-3]. A typical hose assembly is generally composed of a nipple, a socket, a nut and a hose with reinforcement layers to increase the tensile strength [4]. To produce the hose assembly, crimping or swaging process is generally used to clamp its components to ensure the prevention of fluid leakage. Crimping is a cold-working technique to form a strong bond between the workpiece and a non-metallic component [3]. The high pressure hose assemblies are generally crimped, as the crimping process creates more reliable pipe–hose joints than mechanical clamping [4].

All the components involved in crimping process influences the performance of the assembly at the crimp joint by mutually creating proper strain fields at the sealing interfaces [5]. This crimp joint plays very important role during hose flexing operation to avoid key failure modes such as fitting blow off, nipple collapse and compression leakage. Leakage in hydraulic hoses is an important aspect for the prediction of hose life. This can be verified by predictive analysis and an observation through tear down of the hose assembly to validate the leakage path [6]. There is some amount literature available on the fatigue life assessment of hydraulic hose assemblies during impulse testing; similarly there is...
some data available on the optimization of crimp diameter, crimping process, and on the leakage path failure analysis. However, there is a limited amount of research cited on the flexural fatigue performance of the hydraulic hose assemblies [6-8]. In addition to this, no research was cited for the combined effect of thermostatic environment and the mechanical flexing motion on the performance of hose assembly during life testing. When a thermostatic environment is combined with the hose flexibility test, new testing parameters needs to be measured and a new set of variables must to be taken into the equation. The current research investigates this combined effect on the performance of the hose fitting juncture, wire braid reinforcements, over the braid silicone sleeve and hose out-of-plane performance.

2. Experimental Set up

The present study was carried out on 5 test samples of hydraulic hose assembly built per SAE aerospace specification AS1339. The hose flexibility test was conducted using BIMAL-Skydrol Flexing Test Stand. The applicable bend radius was maintained for the test sample during installation.

As shown in Figure 1 and Figure 2, the flexing test set up and hose installation is as per SAE aerospace specification AS2078.

Table 1 below shows the test conditions used during experimentation. The flexing motion of test sample was set at a frequency of 70±10 Cycles per Minute (CPM) with a peak to peak amplitude of 7 inches. The operating and proof pressure of the fluid within the hose was defined per its design specification AS1339. An aviation hydraulic fluid Skydrol-LD-4 per SAE aerospace specification AS1241 was used as a test fluid. The aerospace specification AS2078 recommends for 400,000 flexing cycles, the current test sample meets and exceeds this requirement without any leakage. However, the present study investigates the effect of thermostatic ambient temperature and flexing motion on the test sample when subjected to its life test or 3000,000 numbers of cycles, whichever the first. This fatigue limit of 3000,000 cycles for 4 nos. of Test samples was derived from a reliability goal of 95% using a confidence level of 99%. The thermostatic chamber temperature was maintained to -65°F for Test sample 1 and Test sample 2 with the flexing operation carried out for 3000,000 numbers of cycles. Similarly, Test sample 3 and Test sample 4 were subjected to high ambient temperature of +275°F for the similar 3000,000 number of flexing cycles. Test sample 5 was used for teardown, benchmarking and to compare the test results with cold -65°F and hot +275°F tested Sample. A controlled low temperature of -65°F was maintained during the entire flexing operation using 2 stage refrigeration system and high temperature of +275°F was maintained using “M” shaped heaters mounted on the top of test chamber. The test chamber was equipped with a temperature transducer which was placed 6 inch close to the test specimen to measure the test temperature. Similarly, the test pressure and flexing strokes of the Test sample were measured against the programmed input...
parameter as defined in Table 1 below. The testing process was monitored after every defined no. of cycle, to examine the hose leakage or malfunction.

**Table 1.** Test conditions used for hose flexibility test.

| Test Conditions     | Test Sample 1 and Test Sample 2 | Test Sample 3 and Test Sample 4 | Test Sample 5 |
|---------------------|----------------------------------|---------------------------------|---------------|
| Operating pressure  | 3000±60 psig                     | 3000±60 psig                    | NA            |
| Low temperature     | -65±2°F                          | NA                              | NA            |
| High temperature    | NA                               | +275±2°F                        | NA            |
| Flexing amplitude   | ± 3.5 ±.5 inches                 | ± 3.5 ±.5 inches                | NA            |
| Flexing frequency   | 70 ±10 CPM                       | 70 ±10 CPM                      | NA            |
| Flexing cycles      | 3000,000                         | 3000,000                        | NA            |

All the Test samples were analyzed using metallography and metrology instruments. The hose fitting juncture was sectioned axially using Struer’s Discotom-60/65 table top cutting machine. This hose fitting juncture along with the wire braids was further analyzed using Leica stereoscope with a magnification upto 50X. The microhardness measurements were carried out using Micro-Vicker’s hardness tester. The effect of combined thermostatic test temperature and the flexing motion on the hose routing was carried out using Accura Coordinate Measurement Machine (CMM).

3. Results and Discussions

3.1. Effect on hose-fitting juncture

The end fitting facilitates connection between a coupling and a hose, manifold and a hose or a tube and a hose. Fittings are designed for a specific hose style to meet the requirements of industry specifications for that particular style of hose. The socket is generally crimped with an external crimping force on the OD of hose and nipple to create a sealing and retention mechanism. The fitting juncture provides the sealing against the leakage of fluids and retention against the plug loads generated due to fluid pressure.

![Figure 3. Typical crimp stereograph.](image)

As shown in Figure 3 above, the crimp deformation was measured between the socket and the nipple/OD of the hose for the cold and hot tested samples. These deformations were captured on the stereoscope and measured using image analyzer software. The measured data for the crimp deformation on cold and hot tested sample was further compared against the untested crimp measurements. There were 60 nos. of measurements carried out along the crimp length at an interval of 0.2 inches and for each data point the crimp deformation was noted.
Figure 4. Crimp deformations.

As shown in Figure 4 above, the crimp deformation for both cold (-65°F) and hot (+275°F) tested sample was following similar trend across the length of crimp. However, it was observed that the deformation recorded for the cold tested crimp was moderately higher than that of hot tested and untested crimp. The increased deformation at the cold tested crimp can be further observed with a bulged outer diameter of the sleeve which covers the OD of the socket. The average value of excess deformation for the cold tested sample was measured to 1.83 inches which was 1.06 inches for the untested and 1.43 inches for the hot tested sample respectively. These measurements showed that the cold tested sample experienced 72% increase and the hot tested sample experienced 35% increase in the crimp deformation length when compared to that of untested data. The material used at the crimp zone was 304 austenitic stainless which itself possesses good tensile, compressive and impact properties for subzero application [9]. However, these higher deformations at cold temperature could be because of the combination of subzero temperature -65°F, higher fluid pressure and repetitive motion of flexing for an extensive number of cycles which in turn produced a brittle crimp zone. The another contributing factor could be the reduced toughness of 304 austenitic stainless steel material used at the crimping zone affecting the retention mechanism [8], which would require some more detailed analysis.

3.2. Effect on over the crimp silicone sleeve
Hose cover is typically used over the reinforcement; simply as a protection from environmental damage and it does not add to the pressure capability of the hose, but protects the hose reinforcement from abrasion, moisture, rust, and fire etc. One of the most commonly used cover material for protection against fire is silicone sleeve over the wire braids. As shown in Figure 5 below, it was observed that the repetitive flexing motion for 300,000 numbers of cycles when combined with cold chamber temperature of -65°F resulted into crack along the periphery of the integral silicone sleeve on both the ends of hose fitting juncture which experienced the oscillation impacts during flexing. No crack initiation was observed on the silicone sleeve during high temperature test and on the untested test sample. As silicones are cooled toward their freezing point, they become stronger and elastic, with moderate or slow increase in tensile and adhesion strength while elongation decreases [10]. This decreased elongation of the silicone sleeve at -65°F temperature when combined with the mechanical push-pull effect produced by flexing motion resulted to crack initiation on its surface, which further propagated around its periphery for rest of the fatigue cycles.
3.3. Effect on hose plane
The AIR1569 – Aerospace Information Report recommends single plane routing of the hose to avoid twist or kink leading to hose failure. In current study, the hose out of plane was measured on both cold -65°F and high +275°F tested sample using CMM and the results were compared against that of the untested hose sample. As shown in Figure 6, it was observed that the temperature doesn’t have any specific effect on the associated out of plane induced by mechanical flexing motion for 3000,000 numbers of cycles.

3.4. Effect on fitting material properties
The nut used on the end fitting of hose assembly was the first exposed component to the surrounding temperature and it was manufactured from 304 austenitic stainless steel. The austenitic stainless steels such as 304 grades are considered suitable for subzero ambient temperatures, typically down to -40°C. It is basically the result of 'fcc' (face centered cube) atomic structure of the austenite, which is the result of the nickel addition to these steels [11]. The face-centered cubic structure has less space available for interstitial defects and results in a stronger, more durable material [11]. After the hose assembly teardown, the nut specimen of cold tested sample was sectioned axially along its length and the hardness was measured in transverse direction. As shown in Figure 7, an average increment of 7.5% was observed on the hardness of the cold tested sample when compared to that of untested one.
3.5. Effect on wire braid angle

When an internal pressure is applied to the hose assembly, the forces developed tend to make the hose either elongate or contract (depending on the type of reinforcement and/or braid angle). The effect of braid angle on wire tension and length change can affect the ideal values of the inner and outer braid angles in a particular case [12]. There is a neutral braid angle at which forces exerted are balanced. The wire braid angle was measured for various braids over the hose for both cold and hot tested sample and further compared with that of untested hose.

As shown in Figure 8 above, when the hose is subjected internal fluid pressure and the mechanical motion induced by flexing, this condition tried to move the braid angle toward the neutral angle (54°4′) or angle at which equilibrium is found. The application of additional pressure will continue to stress the reinforcement and assuming that there is no elongation of the reinforcement the reinforcement will ultimately fail and the hose will burst. The braid angle measured for cold tested hose was marginally higher than that of hot tested and untested hose. A further research will be needed.
to investigate the effect of prolonged cold temperature and the associated phenomenon of variation in toughness of the stainless steel wire braids resulting to increased braid angle [11].

4. Conclusions
The present study investigated the flexural fatigue performance of the hydraulic hose assembly when tested to a thermostatic hot and cold temperature combined with mechanical flexing motion till its life or 3000,000 numbers of cycles whichever the earliest. It can be concluded that the combined effect of mechanical flexing for extended number of cycles and the thermostatic cold and hot temperature of -65°F and 275°F did not contribute to hose failure or leakage for the current design. However, at cold temperature of -65°F with prolonged duration of flexing cycles, there was an effect observed on the performance characteristics of the hose fitting juncture with higher amount of crimp deformations (72%) as well as the initiation and propagation of the crack on silicon cover which would result to the hose leakage when tested beyond the defined cycles. It was also observed that the temperature doesn’t have any specific effect on the associated hose out of plane performance induced by mechanical flexing motion. The austenitic stainless steel material used on the hose wire braids and the fittings provides better mechanical properties at subzero temperature, however the effect on toughness further needs to be investigated.

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Acknowledgement
The author gratefully acknowledge the extended support provided to this work by Aerospace, Material and Metrology test lab at EIIC (Eaton India Innovation Center), Pune. The author also acknowledges the support provided by Eaton Aerospace, Jackson-Michigan-United States, for the test sample build. The author would also like to express special thanks to review committee and leadership team of Eaton for granting the permission to publish/present the research work.