Leak-before-break Leakage and Heat Transfer Simulation Of Aircraft Bleed Air System Ducts

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Abstract: *For the safe design of aircraft bleed air system ducts and assessment of ducts with minor cracks found in the quality inspection, it is required to understand and predict the crack behavior and leak-before-break air leakage. A leak before break is desired so a leak can be detected and a repair made before a structural failure. Measuring the leaked air temperature is a widely used technique to detect the leakage flow. The ground maintenance team uses thermal imagining and temperature probe, while the on-board system uses temperature sensor wires to detect the hot air leakage. In this study, the Extended Finite Element Method (XFEM) is used to evaluate if an initial crack will grow into unstable failure. CFD analysis is used to calculate the leak-before-break crack leakage rate and heat transfer (including conduction, convection and radiation) in the case of a stable through-crack, utilizing the crack dimensions obtained from crack propagation simulation. The leakage flow and temperature field prediction enables a better knowledge of the air leakage and heat loss through the crack and provides the design guideline for the duct leakage detection system.*

Keywords: *Aircraft Bleed Air System, Duct, Leak-before-break, Crack Damage Tolerance, Leakage Flow Rate, Extended Finite Element Method, XFEM, Heat Transfer*

1. Introduction

The aircraft bleed air system taps into the main engine compressor or auxiliary power unit for high temperature and pressurized air. The bleed air is used for other applications throughout the aircraft, such as anti-icing system, environment control system, pressurization of water reservoirs, hydraulic reservoirs and pneumatically powered actuators, etc. The aircraft bleed air system consists of ducts, control valves, and heat exchangers. For a large number of aircraft bleed air systems, the duct assemblies are Inconel 718 weldments. Because of its properties of readily fabricated, good tensile, fatigue, creep, and rupture strength, Inconel 718 has been widely used for aircraft air and liquid duct applications. However, in the case of Inconel 718 weldments, crack initiation during conventional welding processes is not uncommon. As such, cracks may initiate or exist in areas of high stress concentration or from material/manufacturing defects.

The initial minor cracks may or may not grow, depending on many factors, such as initial crack size, loading, material strength, etc. If propagation does occur, the cracks may grow resulting in two possible failures: either the crack grows steadily through the wall to form a stable "through-crack" (leak-before-break), or it becomes unstable before or after it has reached the external surface and spreads rapidly over a large portion of the duct (break-before-leak). The catastrophic duct failure may cause adjacent component overheat, aircraft structural damage, wire insulation damage, or even inflight fire. For the safe design and assessment of these ducts for which minor cracks are identified during quality inspection, it is required to understand and predict the crack behavior and leak-before-break leakage rate to determine if a crack can be detected before it reaches a critical size and leads to structural failure.

In this study, the Extended Finite Element Method (XFEM) is used to evaluate if an initial crack will grow into unstable failure. Then, the leak-before-break crack leakage rate and heat transfer (including conduction, convection and radiation) in the case of a stable through-crack are simulated in CFD analysis, utilizing the crack dimensions obtained from crack propagation simulation.

2. Duct Damage Tolerance Assessment

Crack damage tolerance approach, introduced by the United States Air Force in 1985, assumed that flaws can exist in any aircraft structure and such flaws propagate with usage. Aerospace engineering design needs to manage the extension of existing micro cracks in structure through the application of the principles of fracture mechanics. Because of its two major advantages, no need for re-meshing and far more accurate solution with only a small increase in number of degrees of freedom, Extended Finite Element Method (XFEM) is getting more application in crack growth analysis in aerospace structure (Arevalo et al, 2015).

In this study, Extended Finite Element Method (XFEM) is used for crack propagation simulation in aircraft bleed air ducting system. Figure 1 shows the duct geometry and crack considered in the study. An initial crack size is assumed to be located at the most unfavorable position and orientation with respect to fatigue crack growth potential. The modeled cracks are pre-existing or initiated at the duct inner wall surface, along the duct axis direction. This orientation is similar to many cracks found in the quality detection. Only a single defect at the location is considered in the analysis model. Both partial-through and through cracks are studied. The initial maximum size of a partial-through crack should be determined so the crack does not propagate to cause a catastrophic failure during the life of the aircraft. The partial-through crack may or may not break through the wall thickness depending on initial crack size, material strength, and load condition. An assessment is required to ensure that if a crack does propagate through the wall a leak-before-failure condition exists versus a break-before-leak condition. The leakage rate should be determined so that it can be detected by the inspection or onboard aircraft systems to ensure the part can be repaired or replaced before a structural failure occurs.

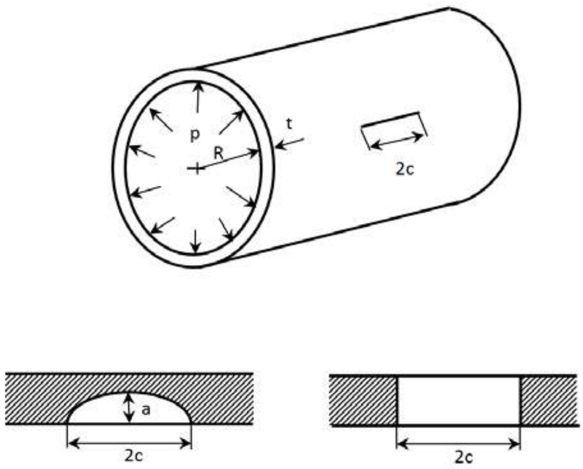

Figure 1. Axial crack considered in a duct (initiate from inside and crack through the thickness).

The crack length and depth can be found from the quality inspection. For analysis, the weld defect crack is assumed to have a semi-elliptical profile. Considering symmetry and crack geometry, one-half segment of the duct is modeled for the finite element analysis. Abaqus' quadratic structural elements, C3D8R, are used in the duct modeling. A finer mesh is used for elements surrounding the initial crack site. The equivalent operating pressure that factors in the known material response to the temperature is applied on the inner surface of the duct. The plug load, $p*0.25*\pi*d^2$, is applied at one end of the duct model. Figure 2 shows an example of typical crack propagation from an initial crack to a through crack.

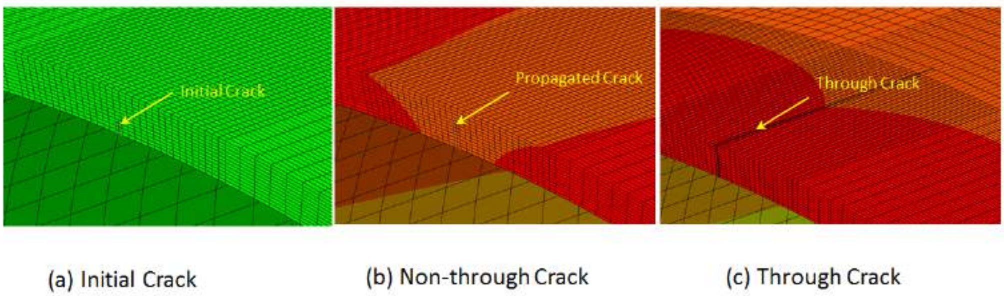

Figure 2. Initial crack and propagation.

The stress intensity factor is calculated in FEA at the crack defect. If the stress intensity factor, ΔK, is smaller than the threshold intensity factor, K_{th}, or $\Delta K < K_{th}$, no crack growth occurs and no crack propagation calculation is needed. If the stress intensity factor is greater than the threshold, $\Delta K > K_{th}$, the crack will begin to propagate.

In the case of $\Delta K > K_{th}$, the crack propagation calculations can be performed using the Paris equation (Paris et al, 1961):

$$da/dN = c\,(\Delta K)^m$$

Where,

da/dN, is the change in crack length per cycle
c, is the Paris Coefficient (ksi^{-m} in$^{(1-0.5m)}$)
ΔK, is the change in stress intensity factor (ksi in$^{1/2}$)
m, is the Paris exponent

The pressure load cycle is defined as the bleed air system is turned on (0 to operating pressure), hold-on at the operating pressure, and then turned off (operating pressure to 0 psi). The loadings, the pressure and plug loads, used in the FEA crack assessment analysis were simply related to pressure loading. The resulting ΔK is therefore equal to K_I for each pressure load cycle.

The K factors at different crack depths were calculated in the finite element model. A best-fit curve function $\Delta K = f(a)$ was used for integration of the Paris equation to get the life cycle vs. crack depth relationship.

$$N = \int_{a_0}^{a_c} \frac{da}{c(\Delta K)^m}$$

Where,

N is the number of life cycle
a_0 is the initial crack depth
a_c is the critical crack depth

The critical crack depth (one component of the maximum allowable flaw size) is the crack depth at which one more load cycle will cause the crack to propagate through the thickness and allow the internal air to escape. The linear elastic fracture mechanics (LEFM) approach in Abaqus utilizes XFEM and Paris' law for assessment of crack growth and correlates well with analytical calculation.

3. Leakage Analysis Approach

In the case of through crack, there is a need to calculate the air leakage flow through the crack. The leakage flow rate is calculated as a function of crack length ranging from the minimum crack length to the critical crack length. The initial through-crack length may be assumed as two-times wall thickness or based on quality control measured data.

Beck et al proposed an idealized crack geometry approach to calculate the leak flow (Beck et al, 2005). Figure 3 shows the idealized crack geometry. The zig-zag shape represents the effect of wall roughness. The assumption is that the angle between metal grain faces is exactly 90 degrees. It was demonstrated that the analytical results have a good agreement with lab test data.

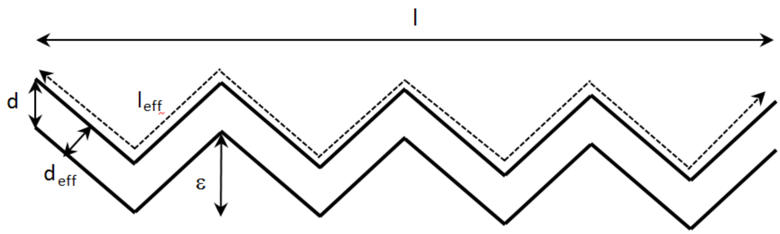

Figure 3. Idealized crack geometry.

The leak flow is divided into 4 regions:

1) Narrow crack, the flow is dominated by the viscosity:

$$u\left[\frac{12\mu l_{eff}}{d_{eff}^2}\right] - \Delta P = 0$$

2) A larger crack, the inertia pressure becomes more important:

$$\frac{\rho u^2}{2}\left[N 2\theta \frac{d_{eff}}{d}\right] + u\left[\frac{12\mu l_{eff}}{d_{eff}^2}\right] - \Delta P = 0$$

3) A further larger crack, the inertia forces are now minor:

$$\frac{\rho u^2}{2}\left[N\left[1-\left(\frac{d_{eff}}{d}\right)^2\right]\right] + u\left[\frac{12\mu l_{eff}}{d_{eff}^2}\right] - \Delta P = 0$$

4) The flow becomes turbulent, the expansion and contraction losses are dominant:

$$\frac{\rho u^2}{2}\left[N\left[1-\left(\frac{d_{eff}}{d}\right)^2\right]\right] - \Delta P = 0$$

A simple 2-D model is created using CFD for leakage flow simulation (Ye, 2016). The simulated leakage flow is compared with the analytical solution. Once the simple geometry CFD model is verified the approach can be used in 3-D model and more complex crack geometries.

Using the crack length and opening calculated in XFEM crack modeling together with the assumption of through crack, the leakage flow rate can be simulated. Figure 4 demonstrates the CFD model of the idealized crack and velocity magnitude plot.

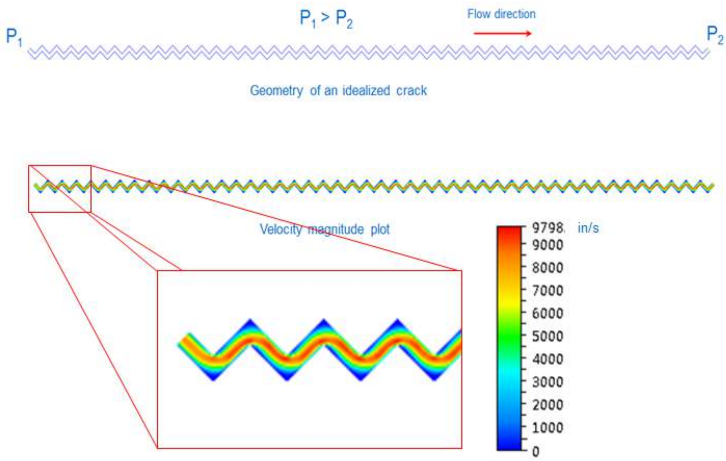

Figure 4. 2-D CFD model of idealized crack.

4. Heat Transfer Simulation

During the aircraft inspection, the ground maintenance team uses techniques, such as hand, hearing, thermal imaging, temperature probe, ultrasonic leak detector, etc. to detect the bleed air leakage. The on-board detecting systems use thermal sensor wire detecting leakage by temperature. One of the important parameter for such detecting system is how far away the sensor wire should be placed above the ducting system surface. The leakage flow and temperature field prediction enables a better knowledge of the air leakage and heat loss through the crack and provides the design guideline for the duct leakage detection system.

Aircraft hot ducting which may expose to leaked fuel or hydraulic oil vapors are usually covered with a thermal insulation layer that prevents the ducting system outer surface from reaching a certain temperature. Figure 5 shows the 3-D thermal analysis model used for simulating the heat transfer in the case of leakage through a through-crack. The through crack dimensions, such as mean width, length, are coming from XFEM crack propagation analysis. The duct is covered with a layer of fiberglass insulation material and a very-thin aluminum outer-foil. It is assumed that the leaked hot, high-speed air will create a flow passage through the fiberglass insulation material and the very-thin aluminum outer-foil with a same dimension of crack length and width.

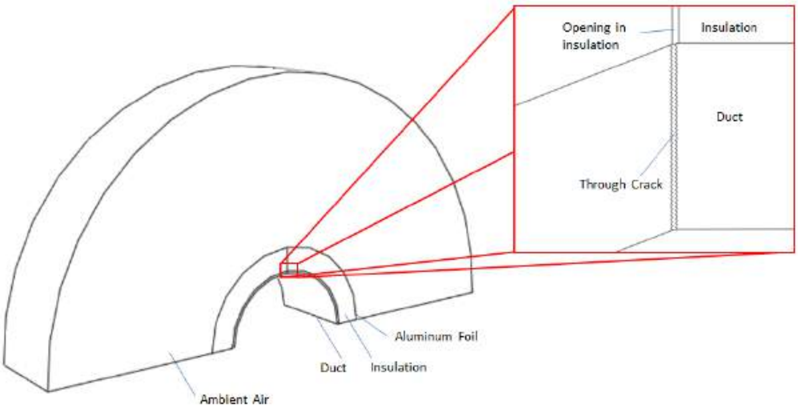

Figure 5. 3-D thermal analysis model.

The operating pressure and temperature are applied to the duct inner diameter, while the ambient pressure and temperature are applied to the outer cylinder surface. The physical phenomena considered include heat conduction, convection and radiation. The simulation is of turbulent flow and steady state condition.

5.Results and Discussion

The considered bleed air duct is made of Inconel 718 material. It has a 5 inch (127 mm) inner diameter and 0.09 inch (2.286 mm) wall thickness. During the flight, the bleed air system may endure different load conditions. A worst scenario simulation is carried out for a specific duct with given initial through-crack lengths. Four cases which cover the operating envelop are studied:

Case 1 at sea level: $T = 700^oF$, $P_1 = 130$ psia, $P_2 = 14.7$ psia;

Case 2 at 41000 ft: $T = 700^oF$, $P_1 = 130$ psia, $P_2 = 2.6$ psia;

Case 3 at sea level: $T = 1200^oF$, $P_1 = 400$ psia, $P_2 = 14.7$ psia;

Case 4 at 41000 ft: $T = 1200^oF$, $P_1 = 400$ psia, $P_2 = 2.6$ psia.

Where: P_1 – pressure inside of duct, P_2 – pressure outside of duct, T – hot air temperature

The crack size under load condition is analyzed with XFEM. The mean grain size, crack length, and averaged width along the length are used in the leakage calculation. The mean grain size, 0.001 inch, is determined from the metallurgy micrograph pictures of Inconel 718 material.

Figure 6 shows a leak-before-break situation analysis result of the duct component. Normalized flow rate is the leakage flow per unit surface crack length. The results show that the effect of pressure at the outside of the duct is small. The curvature and slope variation reflect the leakage flow characteristics as the crack size increases. A comparison of the CFD simulated leakage flow rate with the analytical calculation method proposed by Beck et al shows that both methods predict a similar trend and are quantitatively close.

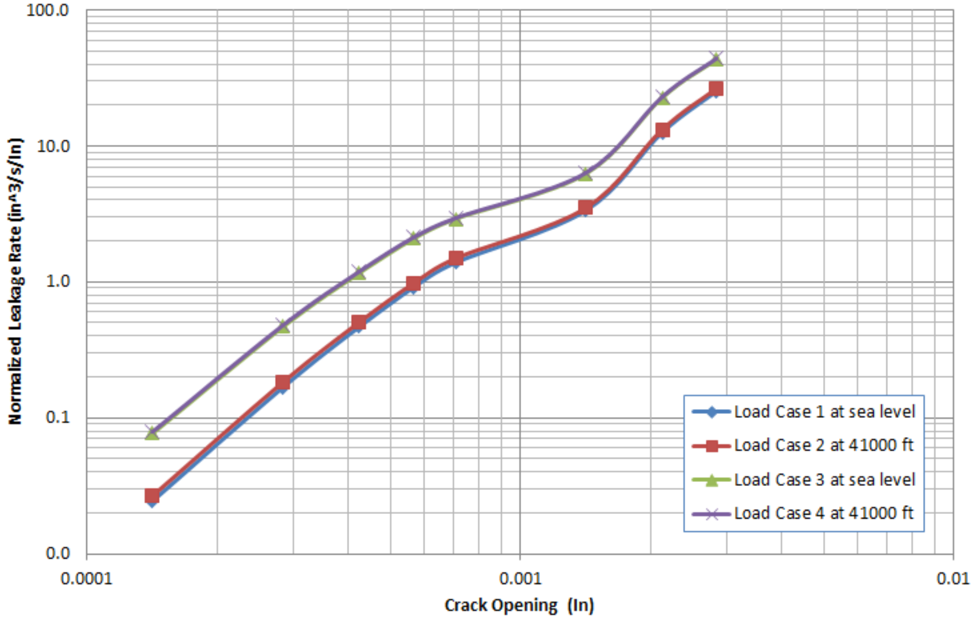

Figure 6. Leakage rate prediction.

A typical result of temperature field and cross-section view is shown in Figure 7. The ducting system surface touch temperature that is an important parameter for duct insulation design and the temperature decay out of the crack can be obtained from the analysis results.

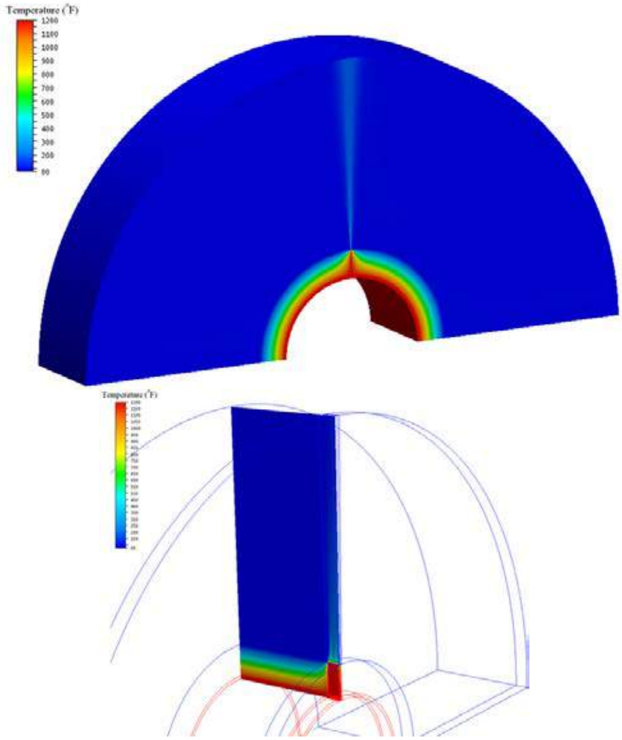

Figure 7. Temperature distribution out of through crack.

The temperature distribution along the leakage axis is shown in Figure 8. In this analyzed case, the crack half-length is 0.335 inch (8.5 mm), crack width is 0.004 inch (0.1 mm). Duct wall thickness is 0.09 inch (2.286 mm). Fiberglass insulation thickness is 0.9 inch (22.86 mm).

Figure 9 shows the temperature variation with the distance away from the duct inner diameter (ID) surface. The temperature drops rapidly starting from the duct insulation outer surface.

Figure 10 demonstrates the effect of duct inner operating pressure on the temperature distribution. The lower the pressure, the quicker the temperature drops.

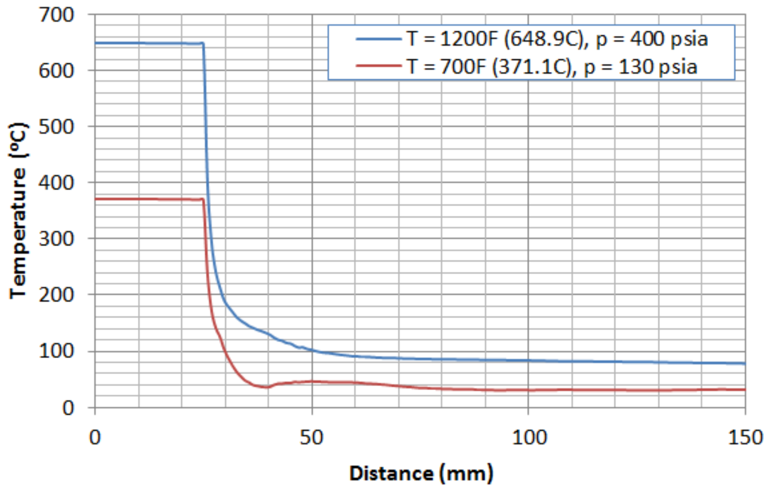

Figure 8. Temperature distribution out of through crack.

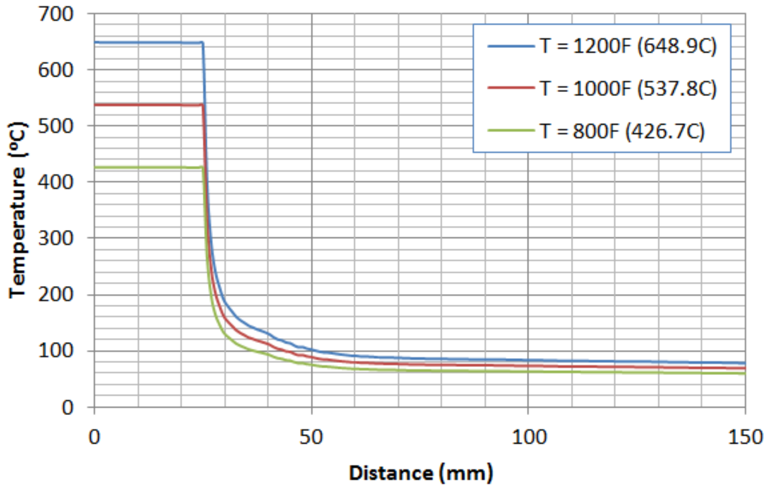

Figure 9. Effect of operating temperature on temperature distribution.

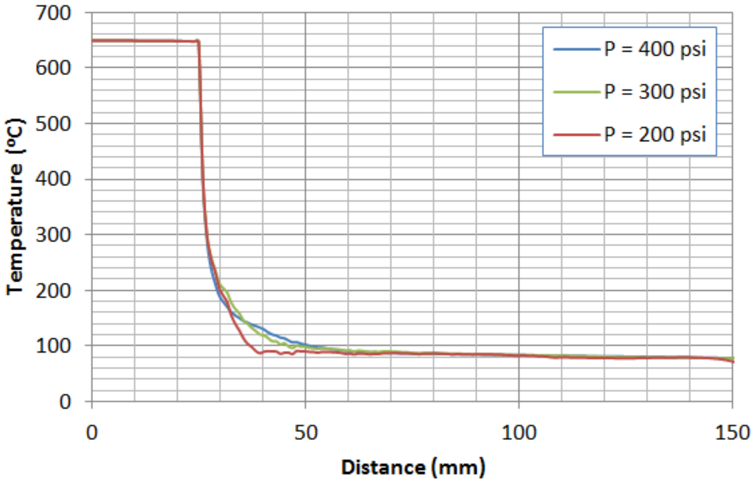

Figure 10. Effect of operating pressure on temperature distribution.

The leakage detecting system design is largely depend on lab test to determine the design parameters and detectable leakage rate. The prediction of crack size, leakage rate and temperature field is of valuable help in the design process. For example, once the sensor triggering temperature is set, the sensor positioning distance away from the insulation surface can be determined from result shown in Figure 9.

6. Conclusion

This paper studied the aircraft ducting leak-before-break situations with a combination of FXEM and CFD thermal analysis. The Abaqus XFEM simulation is an efficient tool for the assessment of allowable preexisting defect size and predicting the crack size under load. The CFD analysis provides a reasonably accurate leakage flow and heat transfer predictions in the case of leak-before-break situation. The analysis results are very useful for the detectable leakage rate prediction for thermal sensor system and the design parameter selection for such system.

6. References

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