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Theoretical Research on Identification Method of Fatigue Crack Tip in Aeronautical Materials Based on Infrared Thermography

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Abstract. Early identification of fatigue cracks in aerospace materials represents a crucial aspect of maintaining flight safety. Accordingly, this study examines methods for detecting fatigue cracks through the application of Infrared Thermography (IRT). Notably, together with the development of a comprehensive theoretical model designed to explain and predict the detection of fatigue crack tips in aerospace materials, it introduces a novel framework for crack identification derived from this model. By combining principles from material mechanics and fluid mechanics, a theoretical framework is established to characterize the thermo-mechanical-fluid multi-field coupling behavior at crack tips under cyclic loading, with a detailed analysis of the effects of plastic work heat, thermoelastic responses, and convective cooling on crack tip temperature. In addition, the thermo-mechanical coupling at crack tips is investigated comprehensively, incorporating spatiotemporal feature fusion together with deep learning algorithms. Theoretical results indicate that the model can accurately characterize the temperature field at crack tips, thereby enabling high-precision identification of micro-cracks. Besides, the proposed identification framework shows strong reliability even under complex airflow conditions.

Keywords: Infrared Thermography, Fatigue Crack, Crack Tip Identification, Theoretical Model, Deep learning algorithm

1. Introduction

The detection of fatigue cracks in aerospace materials plays a key role in maintaining flight safety as such cracks compromise the structural integrity of aircraft. Therefore, accurate identification of crack tips is particularly important for effective structural health monitoring (SHM). Despite their widespread use, traditional techniques like ultrasonic testing and X-ray imaging are constrained by complex procedures, slow processing, and insufficient real-time monitoring [1,2]. In recent years, infrared thermography (IRT) has become a prominent non-contact, full-field, real-time method for non-destructive evaluation, offering promising applications in the aerospace field [3]. Moreover, it can detect changes in surface temperature distributions, revealing internal defects and crack growth, making it well-suited for online monitoring of complex aerospace structures. However, IRT still encounters practical challenges, such as fragmented spatiotemporal dimensions in thermal sequence

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processing that limit feature extraction, and airflow-induced cooling in aerospace environments that disrupts surface temperature distribution. Because of the small size of micron-scale cracks, the thermal signals emitted from these cracks are weak and are overwhelmed by background noises [4,5]. Therefore, in order to solve the above two problems, this paper combines the material mechanics and engineering fluid mechanics to establish a theoretical model of thermo-mechanical coupling around the tip of the cracks, and explains the process of heat generation and dissipation; meanwhile, an original crack identification framework based on spatiotemporal feature fusion and deep learning algorithms is proposed to enhance the accuracy and reliability of crack tip extraction. Thus, this study attempts to establish a theoretical model which plays the role of theory basis and methodological guidance in the quantitative application of infrared thermography technology in aerospace NDT. It is expected that this study could provide theoretical support and technical reference for the application of infrared thermography technology in the detection of fatigue cracks of aerospace materials, and could also provide theoretical basis and technical guidance for the development of structural health monitoring technology of aircraft.

2. Related work

Compared with IRT, DRT can measure not only temperature but also the distribution of other material parameters. IRT, which is realized by detecting the infrared radiation, can be widely used in NDT. And this method can realize the non-contact, full-field, real-time temperature measurement and defect location and application to the fatigue crack detection in aerospace material [6,7]. IRT obtains the visualized temperature field image of the object by collecting the infrared radiation from the object's surface. According to Planck's law, the object emits infrared radiation even if its temperature is above the absolute temperature [8]. The optical system of the infrared camera collects the infrared radiation and focuses it on the detector, where the radiation is transformed into electric signals. Finally, the two-dimensional map of temperature distribution is generated by post-processing the electric signals, for instance, the non-uniformity correction and temperature inversion.

In terms of implementation, the IRT techniques can be classified into passive method and active method. In the passive thermography, the detection is based on the object's own temperature field or surrounding environmental temperature gradient, which is usually applied in the equipment in operation. While in the active thermography, different from the passive thermography, Electro-Convective Pulse Thermography (ECPT) heats the test sample with thermal excitation from the extra input energy, which leads to the thermal perturbation propagating in the material and inducing temperature variation in the vicinity of defect [3]. When reaching the crack tip, the heat flow would be concentrated at the tip with limited lateral heat diffusion, which results in typical thermal patterns such as linear thermal fringes or discrete hotspots near the crack tip [4]. The thermal patterns help to locate the crack and further, different geometric and mechanic information of the crack can be extracted by analyzing the spatiotemporal distribution of the cracks.

Although IRT has a few advantages in theory, there are still some problems existing in the application. The spatiotemporal dimension is divided into fragments in the thermal sequence process, which makes it hard to extract effective features; airflow will lead to cooling effect on the surface temperature in aerospace field [4,5]; the thermal signal generated by micron level cracks is weak and is affected by noises. Therefore, these problems make the effectiveness of current IRT method in aerospace material fatigue crack detection hard to be realized and the crack tip position is hard to be located accurately. Thus, most of the current researches on the improvement of IRT are devoted to the optimization of signal processing method, improving the accuracy of IRT crack

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detection and heating method. The application of advanced image processing technique, especially the deep learning based algorithm, can significantly improve the accuracy and efficiency of the crack identification. Besides, refinements in thermal excitation technique, like vibrothermography which applies vibrational stimuli at certain frequency to enhance the thermal signal at the tip of crack, are also adopted to improve the IRT method.

3. Theoretical modeling and analysis

3.1. Thermo-mechanical-fluid coupling theory at crack tip

The crack-tip temperature field arises from coupled thermo-mechanical and convective interactions. These coupled effects define the thermo-mechanical-fluid environment at the crack tip. From the standpoint of material mechanics, the stress intensity factors K_I and K_{II} characterize the local stress field near the crack tip under mixed-mode loading. The corresponding crack-tip normal stress can be expressed as:

$$\sigma_y(r,\theta)=\frac{K_I}{\sqrt{2\pi r}}f_y(d)+\frac{K_{II}}{\sqrt{2\pi r}}g_y(d)+\sigma_{thermal} \tag{1}$$

where $f_y(d)$ and $g_y(d)$ are functions of crack-tip geometry and distance, r is the radial distance from the crack tip, and $\sigma_{thermal}$ represents any thermal stress contribution due to temperature changes. This stress distribution determines the extent and intensity of the plastic zone at the crack tip. Under cyclic loading, the plastic zone absorbs a large amount of mechanical energy, part of which is converted into thermal energy, thus producing a local temperature rise that can be described by the thermoelastic equation.

$$Pc\frac{\partial T}{\partial t}=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+q \tag{2}$$

where P is the material density, c is the specific heat capacity, k is the thermal conductivity, and q is the heat source, mainly originating from plastic work caused by crack propagation [9]. This equation allows analysis of the temporal and spatial distribution of crack-tip temperature.

In addition, the crack-tip temperature distribution is influenced by material thermal properties. As illustrated in Table 1, the density, specific heat, and thermal conductivity of different aerospace materials determine the heat diffusion rate and local temperature rise at the crack tip [10].

Table 1. Thermodynamic parameters of typical aerospace materials

Material	Thermal Conductivity (W/m·K)	Specific Heat (J/kg·K)	Density (kg/m³)	Thermal Diffusivity (m²/s)
Titanium alloy 7075	130	960	2810	4.8×10^{-5}
Titanium alloy Ti-6Al-4V	6.7	560	4430	2.7×10^{-6}
Nickel-based alloy 718	11.4	435	8190	3.2×10^{-6}

From an engineering fluid mechanics perspective, high-speed airflow alters the heat dissipation efficiency at the crack tip, which can be described by the boundary-layer convection equation.

$$P_e\frac{\partial T}{\partial t}=\nabla(k\nabla T)+q_p\text{-}h_c(T\text{-}T_m) \tag{3}$$

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where ∇ is the spatial gradient operator, q_p is the local heat source, h_c is the convective heat transfer coefficient determined from boundary-layer theory, and T_m is the airflow temperature. The convective heat transfer coefficient for a laminar boundary layer is given by:

$$h_c = 0.332 \times \frac{k}{L} \times Re^{\frac{1}{2}} \times Pr^{\frac{1}{3}}, \quad (Re < 5 \times 10^5) \tag{4}$$

and for a turbulent boundary layer:

$$h_c = 0.0296 \times \frac{k}{L} \times Re^{\frac{4}{5}} \times Pr^{\frac{1}{3}}, \quad (Re > 5 \times 10^5) \tag{5}$$

where k is the thermal conductivity of the fluid, L is the characteristic length, Re represents the local Reynolds number, and Pr is the Prandtl number. These expressions are derived from classical boundary layer theory for forced convection over a flat plate. Consequently, the convective heat transfer coefficient h_c quantifies the efficiency of heat exchange between the crack surface and the surrounding airflow, and its spatial distribution can significantly influence the temperature field at the crack tip.

3.2. Thermodynamic model of the fatigue crack tip

Based on the previous thermo-mechanical-fluid coupling framework, the thermodynamic model of a fatigue crack tip quantifies the link between cyclic mechanical loading, local plastic dissipation, and the corresponding thermal response [11].

During fatigue crack propagation, cyclic stress concentration induces plastic deformation in a small region ahead of the crack tip. The local heat source is generated by plastic work, expressed as:

$$q = \eta \, \sigma_y \, \dot{\varepsilon}_p \tag{6}$$

where η is the thermal conversion efficiency, σ_y is the normal stress at the crack tip, and $\dot{\varepsilon}_p$ is the plastic strain rate [12]. For aluminium and titanium alloys, experimental data indicate that η typically lies between 0.6 and 0.8. In the present study, an upper-bound value of 0.85-0.95 is adopted to represent the theoretical maximum under idealised (near-adiabatic) conditions, providing a conservative estimate of the largest detectable thermal signature. The transient temperature field is then obtained from the heat-conduction equation, yielding the spatial and temporal distribution $T(x,y,t)$ near the crack tip and enabling evaluation of the thermal signature under fatigue loading.

Under aerospace operating conditions, forced convection caused by high-speed airflow greatly affects the surface temperature field. The key environmental factors influencing crack-tip thermal signals are summarized in Table 2.

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Table 2. Factors affecting crack thermal signal by airflow environment

Factor	Influencing mechanism	Effect
Flow velocity	Change the convective heat transfer coefficient	High velocity flow enhancement cooling reduces signal-to-noise ratio
Boundary layer state	Transition from laminar to turbulent flow affects heat transfer efficiency	Turbulence increases thermal fluctuations and covers up crack hot spots
Mach number	High Mach number produces aerodynamic heating	Temperature rise caused by possible confusion with cracks
Angle of attack	Affect flow separation and reattachment	The surface temperature is not evenly distributed

To quantitatively describe the interaction between fatigue crack geometry, loading conditions, and temperature evolution, a semi-empirical correlation can be introduced:

$$\Delta T = f(K, a, \Delta\sigma, N) \tag{7}$$

where ΔT is the local temperature rise, K is the stress intensity factor, a is the crack length, $\Delta\sigma$ is the cyclic stress amplitude, and N is the number of load cycles. The function $f(\cdot)$ captures the combined influence of mechanical driving force and convective cooling. This model provides a theoretical foundation for predicting the infrared thermal response associated with fatigue crack propagation, enabling a quantitative link between temperature signals and crack growth.

3.3. Practical feasibility and signal enhancement

The thermal characteristics of fatigue cracks essentially develop synchronously in both spatial and temporal dimensions, thus reflecting the transient heat transfer process at the crack tip. However, conventional approaches that analyze individual frames or single-point time series are unable to fully capture this spatiotemporal evolution, resulting in information degradation. By considering the thermal sequence in its entirety, spatiotemporal features associated with heat-wave propagation can be extracted, improving the detectability of weak crack signals [5]. Nevertheless, even when employing spatiotemporal analysis, micro-cracks emit weak thermal signals (0.1-0.5 K), whereas noise levels remain nearly constant, resulting in a low signal-to-noise ratio (SNR). At this stage, the measured temperature can be dynamically compensated according to knowledge of the convective environment.

$$T_{comp}(x,y,t) = T_{measured} + \frac{h_c(x,y)}{\rho c_p}\Delta t \tag{8}$$

This compensation improves the effective SNR of micro-cracks, enhancing detection sensitivity. To further quantify detection reliability, a sensitivity analysis of key parameters can be conducted, for example:

$$SNR_{comp} = \frac{T_{crack} - T_{comp}}{\sigma_n} \tag{9}$$

Such analysis clarifies the influence of different aerodynamic conditions (e.g., high flow velocity, boundary-layer state, Mach number, and angle of attack) on the crack-tip thermal signal. In addition,

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since micro-crack signals are affected by environmental noise, the measured temperature can be treated as a random variable:

$$T_{measured}=T_{crack}+n(x,y,t),\quad n\sim N(0,\sigma_n^2) \tag{10}$$

Integrating this with the compensated SNR, the probability of crack detection can be quantified:

$$P(SNR_{comp}>threshold) \tag{11}$$

This provides a quantitative basis for evaluating the detectability of micro-cracks under realistic aerospace operating conditions. Meanwhile, the thermal diffusion length $L_{diff}=\sqrt{4\alpha t}$, $\alpha=\frac{k}{\rho c_p}$ can be used to describe the propagation of the thermal wave in the material. When combined with the crack length a and the number of load cycles N, it allows evaluation of signal observability under different thermal diffusion times.

High-velocity airflow at high altitude alters the convective heat transfer efficiency at the crack tip surface, and this change can be expressed as a function of the local Reynolds number, Mach number, angle of attack, and flow velocity [12,13]:

$$h_c=f(V,Re,Ma,AoA) \tag{12}$$

By applying a compensation formula, the SNR distribution of the crack tip thermal signals under different flight conditions can be quantitatively estimated, enabling dynamic management of signal attenuation and microcrack detectability. By integrating spatio-temporal feature extraction, microcrack signal enhancement, and environmental compensation, a complete workflow has been established for evaluating and enhancing the effectiveness of infrared thermography for crack tip detection in aerospace materials.

4. New optimization scheme for crack tip identification algorithms

Based on the previously established coupled heat-force-flow model, a theoretical scheme for crack tip infrared thermography identification is proposed. The proposed methods are optimized on the basis of this theoretical framework, and the relevant physical mechanisms, mathematical models, and algorithmic structures are clarified. They are able to enhance the thermal contrast of crack tips, capture spatio-temporal features, and maintain robustness under complex conditions.

4.1. Optical flow-based spatio-temporal fusion thermography

In conventional methods, crack tip identification relies only on the spatial temperature gradient of a single-frame thermogram. As a result, these methods are sensitive to noise and have limited ability to detect weak signals from microcracks less than 0.5 mm in length. In contrast, Spatio-Temporal Fusion Thermography (STF-Thermography) boosts thermal contrast by combining spatial gradients with temporal dynamic features [4]. It is based on the fact that the thermal field induced by plastic deformation at the crack tip is spatially localized and temporally continuous. Under cyclic loading, the thermal signal stays within the micron-scale region and evolves continuously with each loading cycle.

The optical flow method captures dynamic changes in temperature by calculating pixel motion vectors between frames of a continuous temperature profile. Fusing these vectors with the spatial

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temperature gradient of each frame highlights regions with both spatial anomalies and temporal continuity, corresponding to microcrack tips. Meanwhile, random spatial noise like electronic noise and transient perturbations such as airflow fluctuations) are suppressed, resulting in an improved SNR.

The infrared thermal sequence is modeled as a three-dimensional data body. The pixel motion vector field (u, v) is calculated using optical flow algorithms like Lucas-Kanade, and its magnitude represents local temperature variation. Within the crack tip region, this magnitude is higher than in the surrounding area due to the continuous heat generation. The spatial temperature gradient ∇T is then weighted and fused with the optical flow amplitude, forming a spatio-temporal gradient field:

$$STGradient=\alpha\cdot|\nabla T|+(1-\alpha)\bullet\sqrt{u^2+v^2} \tag{13}$$

where the weighting coefficient α, typically between 0.6 and 0.8, balances the contributions of spatial and temporal information. This method zooms in to show regions of spatial and temporal anomalies while mitigating one-dimensional noise. By integrating spatial and temporal information, the SNR can theoretically be increased by 30-50%, enabling the detection of sub-millimeter microcracks smaller than 0.3 mm. Its robustness to spatial noise and transient disturbances reduces the need for complex denoising procedures. In addition, this spatio-temporal fusion method is applicable to any transient thermography problem presenting spatio-temporal evolution and has a wide range of analytical uses.

4.2. The vibration thermography with multi-field excitation

Traditional infrared thermography relies on plastic-work heat sources, which generate only weak thermal signals during stable crack propagation or in high-thermal-conductivity materials. Vibration thermography superimposes a controlled vibration to promote relative sliding between the crack faces. Under sustained crack-face contact and macroscopic slip, with adequate closure stress and clean interfaces, frictional energy dissipation can exceed plastic-work heating by a factor of 10-100. This process can induce a local temperature rise of 2-5 K, thus substantially enhancing the thermal contrast at the crack tip. By tuning vibration frequency and amplitude, frictional heat concentrates at the crack tip while limiting bulk specimen heating.

The process is modeled as a coupled mechanical-thermal problem. In particular, the vibration field, with frequency f and amplitude A, is converted into frictional heat $q_{friction}$ via a crack-face contact-mechanics model. Subsequently, this heat is incorporated as an additional source term in the heat conduction equation:

$$\rho c_p \frac{\partial T}{\partial t}=k\nabla^2 T+q_{plastic}+q_{friction}-h_c(T-T_\infty) \tag{14}$$

where q_p represents the plastic dissipation heat. To enhance this effect, optimization of the parameters f and A maximizes crack-tip temperature rise while avoiding uniform heating. In parallel, resonance modes are identified through theoretical and numerical analysis to localize frictional heating at the crack surface. At the data-processing level, frictional heat is separated from mixed signals by synchronizing vibration with thermal image acquisition and applying image registration to correct rigid-body displacement, allowing precise extraction of local high-temperature regions.

Building upon this approach, vibration thermography offers active signal enhancement, allowing direct control over the thermal intensity at crack tips and mitigating the limitations of passive

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detection under weak-signal conditions. It is particularly suitable for materials with a strong crack closure effect, low plasticity (e.g. high strength steels and composites) or high thermal conductivity (including copper and magnesium alloys). Energy limitations ensure operational safety by maintaining excitation well below the material's yield strength (<10%), preventing structural damage. Moreover, this framework can be integrated with the previously developed aero-thermal model to predict performance under high-speed airflow, illustrating its predictive capability under realistic aerospace conditions.

5. Conclusion

This study examines the theoretical analysis and methodological innovation for identifying fatigue crack tips in aerospace materials. In particular, a thermo-mechanical-fluid multi-field coupling model is established to describe temperature field characteristics at crack tips under cyclic loading, including plastic work heat, thermoelastic effects, and convective cooling, providing a theoretical basis for precise crack-tip identification. Based on this model, a crack identification framework is proposed that combines spatiotemporal feature fusion with deep learning. Within this framework, the STF thermography method markedly enhances the SNR of micro-crack thermal signals, while vibration thermography amplifies the signal via multi-physical field excitation, enabling effective detection of micro-scale cracks under complex airflow conditions. In addition, this study provides a detailed analysis of crack-tip thermo-mechanical behavior and establishes a basis for quantitative infrared thermography in aerospace non-destructive testing. The proposed framework is applicable to anisotropic composite materials and complex load spectra, improving the precision and reliability of IRT-based crack detection under realistic aerospace conditions.

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