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# Data Fusion for Combining Techniques to In Situ Detect Defects of Turbine Blade

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## Abstract

In non-destructive testing (NDT) it is important to have a high probability of detection (POD) and reliable characterization of each defect. This can be gained by using several techniques, which leads to an increase in cost and time for testing. Another option is to use several techniques combined into a single probe, in which case data fusion for the techniques is possible. A dual probe containing an eddy current probe and a borescope is presented. These two techniques are complementary , and no detrimental interference is observed. This dual probe can in situ detect defects of complicated object such as aeroengine, which can reduce the need for costly teardown. Turbine blade is one of crucial parts in aeroengine. Defects of turbine blade would endanger flight security. Cracks and corrosion are primary defects of turbine blade. Cracks and corrosion are detected in situ using eddy current and borescope simultaneity. Based on the Dempster-Shafer (D-S) theory of evidence, a decision level data fusion was used to combine probability mass values from borescope and eddy current. The final classification results were obtained by making decisions based on the maximum belief of the fused results. The experimental results show that the high reliable characterization of defect is gained using the data fusion.

**Keywords:** Data Fusion, Borescope, Eddy Current Testing, Turbine Blade, D-S Theory, Non-destructive Testing

## 1. Introduction

In NDT it is important to have a high probability of detection and reliable characterization of defects [1-3]. When more than one technique is used for inspection in order to gain this increased reliability the time for investigating a sample and the cost of the inspection are increased. Further increases in the inspection time come from analyzing the results of all techniques independently. Combining several techniques within one probe has several benefits. Firstly, the inspection time is reduced as only one scan of the sample is required, with a corresponding reduction in cost. Secondly, the cost of inspection may be further reduced if the techniques are able to share hardware, for example the computer for saving and analysis of results. Finally, if the analysis is done concurrently, increased accuracy of information about the defects could be found through competitive data fusion [4,5].

Borescope and eddy current are two complementary NDT techniques. Borescope inspection belongs to visual inspection. It provides a means of detecting and examining a variety of surface, such as corrosion, contamination, surface finish, and surface discontinuities. Borescope allows the inspection of surfaces inside narrow tubes, walls, ducts, large tanks, other dark areas, or difficult-to-reach chambers [6]. Borescope is used in equipment maintenance programs, in which borescope can reduces or eliminate the need for costly teardowns. But borescope inspection has some limitations. Borescope inspection can only detect surface macroscopical flaws, cannot detect jerkwater flaws, and cannot evaluate the depth of cracks. Eddy current testing need not use coupling medium, so can detect defects quickly. It is sensitive to surface and subsurface flaws of metal material and can evaluate the depth of cracks [7]. But eddy current testing has limitations too. When the interface between the eddy current probe and the object cannot come into view, it is hardly to operate correctly. It has dual advantages to combining borescope and eddy current into a probe. The POD is higher when using both techniques together than with each alone. Further information about samples is possible by taking into account the particular strengths and weaknesses of each technique.

## 2. the Dual Probe Design

The dual probe has been design to hold a borescope and an eddy current probe. The individual sensors are described below, and a description of dual probe follows.

### 2.1 Eddy Current Sensor

The constructed eddy current system consists of probe, a coil driver, a signal conditioning circuit, data acquisition card and a PC to process the signals and present the output to the user. The probe adopts uniform eddy current probe which is sensitive and lift-off noise free [8,9].

The uniform eddy current probe is composed of a large exciting tangential coil and a small detecting pancake coil as shown in Figure 1. The wide and large exciting tangential coil generates uniform magnetic field right under it. The direction of the magnetic field $H$ is perpendicular to that of the exciting coil current density $J_0$ based on Ampere's law

$$\nabla \times H = J_0 \qquad (1)$$

The magnetic field generates magnetic flux density $B$

$$B = \mu H \qquad (2)$$

Where $\mu$ is magnetic permeability. Variation of $B$ generates electric field $E$ based on electromagnetic induction

$$\nabla \times E = -\partial B / \partial t \qquad (3)$$

The electric field induces eddy current $J_e$ in conducting material of conductivity $\sigma$.

$$J_e = \sigma E \qquad (4)$$

Thus the eddy current is induced perpendicularly to the magnetic flux.

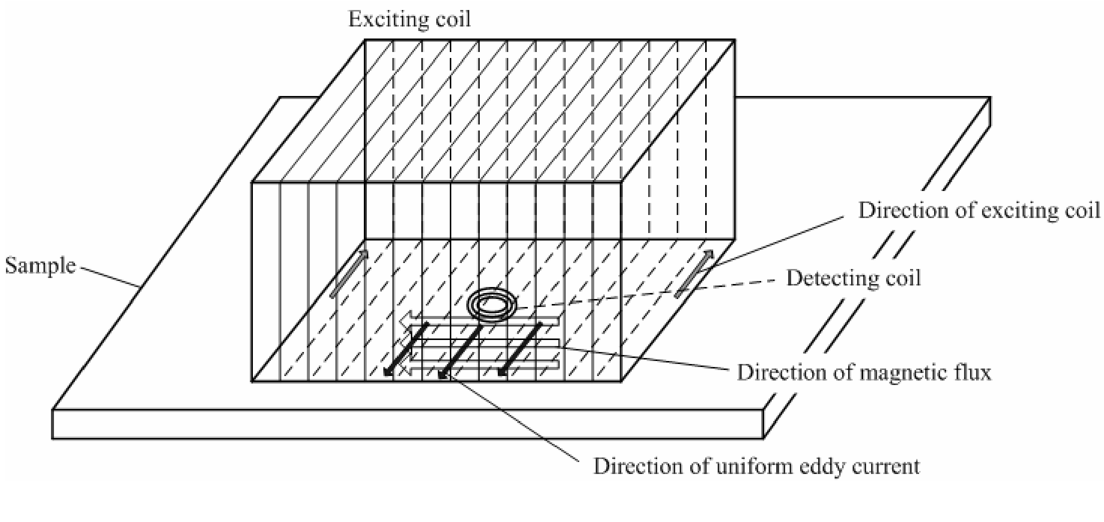


Fig.1 the Uniform Eddy Current Probe

When the sample material has no flaw, the magnetic flux is parallel to the material surface and the detecting coil generates no signal because it picks up only vertical magnetic flux. When the sample material has a flaw, some vertical magnetic flux passes through the detecting coil. The detecting coil generates flaw signal $V$ picking up the vertical magnetic flux $\phi_n$

$$V = -N \partial \phi_n / \partial t \qquad (5)$$

Where $N$ is the number of turns.

**2.2 Borescope**

A borescope is a long tubular optical device that illuminates and allows the inspection of surfaces inside narrow tubes or difficult-to-reach chambers. The video borescope is a new kind borescope. The video borescope used image sensor and transmits images to a video monitor which would reduce eyestrain. The video borescope is mainly composed of illuminant, lenses and image sensor. In this paper, the illuminant adopts two white LED as shown in figure 2(a). The outer diameter of the borescope is 10mm. The lenses adopts a reverse-telephoto configuration[10] as shown in figure 2(b).It has character such as large angle of view, large depth of field, low distortion, long back working distance, large relative aperture, and small exterior size. Image sensor adopts CMOS image sensor which output is digital video. CMOS Image sensor uses OV7670 camera chip of OmniVison. The OV7670 camera chip is a low voltage CMOS image sensor that provides the full functionality of a single-chip VGA camera and image processor in a small footprint package. Its output is digital video signal. The available array element is 640×480, the pixel size is 3.6μm×3.6μm, and the image transfer rate is 30fps.

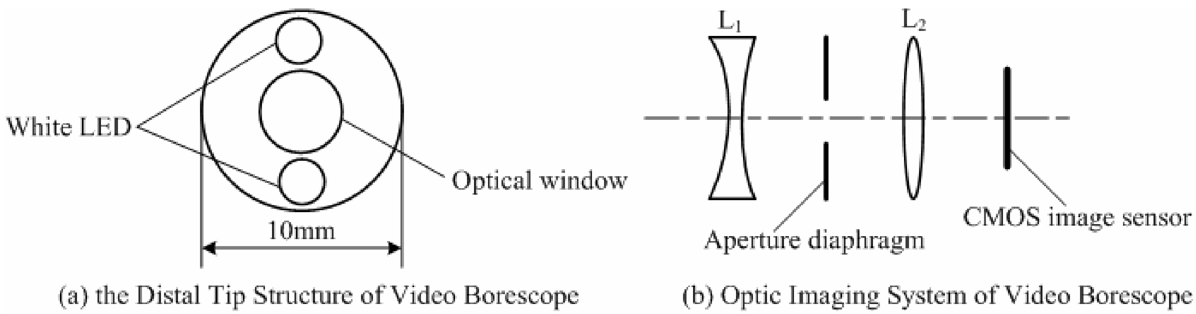


Fig.2 the Partial Structure of Video Borescope

**2.3 Dual Probe**

Figure 3 shows the design of the dual probe. The borescope is placed in the front. User can observe the image of the sample through borescope which can make the eddy current probe scanned over the sample exactly. The borescope is flexible and rotatable. The eddy current probe is placed in the bottom side of supported shank which can make the lift-off between probe and sample decrease. No interference was found between the two systems.

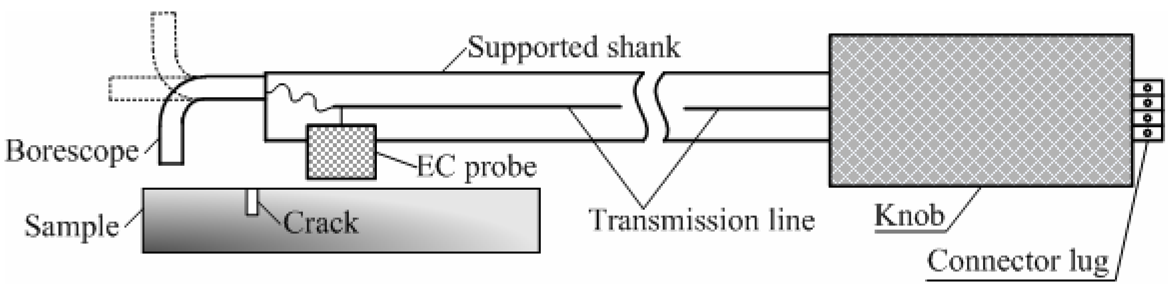


Fig.3 the Dual Probe Design

**3. Data Fusion**

When multiple inspections provide complementary information about the specimen, combining the data may facilitate the analysis or classification process. Data fusion techniques provide a framework to fuse and integrate information from multiple sensors or sources. D-S theory is one of the data fusion approaches that provide a mechanism to fuse information from multiple sources [11,12].

**3.1 the D-S method**

The D-S theory offers a model to the knowledge about one or more hypothesis. This model enables to quantify such concepts as imprecise measurements or uncertainty. The parameter used to perform this description is the evidence mass associated to each event. The core of the D-S method contains three aspects: the concept of probability mass, belief function, and updating mechanism. The frame of discernment $\theta$ is a finite set of propositions that are mutually exclusive and exhaustive. The power set of $\theta$ is $2^{\theta}$, and the elements of this set are all subset of $\theta$. The mass function assigns degree of belief across the set of all subsets of $\theta$, such that,

$$\begin{aligned} & m: 2^{\theta} \rightarrow [0,1], m(\phi) = 0 \\ & \sum m(A) = 1, A \subset 2^{\theta} \end{aligned} \quad (6)$$

The quantity $m(A)$, know as basic probability assignment, is a real number between zero and one. It represents the exact belief committed to $A$. A function "Bel" is called a belief function if it satisfied the following condition:

$$\begin{aligned} & Bel: 2^{\theta} \rightarrow [0,1], Bel(\phi) = 0 \\ & Bel(A) = \sum_{B \subset A} m(B), \forall A \subset \theta \end{aligned} \quad (7)$$

$Bel(A)$ is real number between zero and one that represents a degree of support that the available evidence provides for $A$. Given a belief function $Bel(A)$, the function $Dbt(A) = Bel(-A)$ is called a doubt function and represents the total support for the negation of a proposition. The plausibility function of $A$, denoted by $pl(A)$, is written as $pl(A) = 1 - Dbt(A)$.

Assume the current state of the system has the value $m_1(A_i)$ assigned to all the subsets of $\theta$, and represents the total support from all the previous evidence. The observation of a new distinct piece of evidence by a mass function $m_2$, distributes a new set of mass values $m_2(A_j)$ over the set of $2^{\theta}$. These new mass value $m_2$ and old value $m_1$ are combined to produce update value $m_{12}$. The updating mechanism is performed by:

$$m_{12}(A_k) = \frac{\sum_{A_i \cap A_j = A_k} m_1(A_i).m_2(A_j)}{1 - \sum_{A_i \cap A_j = \phi} m_1(A_i).m_2(A_j)} \quad (8)$$

Where $m_{12}$ is called the orthogonal sum and can be written as $m_{12} = m_1 \oplus m_2$. Formula (8) is called the D-S rule of combination. The crucial problem of using D-S is how the mass function distributes the mass values among the subset of the frame of discernment. Unfortunately, D-S theory does not give the answer. The procedure largely depends on the application.

**3.2 the Procedure of D-S Based Data Fusion**

The procedure that was used for fusing borescope and eddy current data is given in figure 4. To relate the measure data to flaw (material loss), one can use a straightforward calibration approach. That is, given a measurement, find the material loss corresponding to that measurement using a calibration curve. However, a measurement does not uniquely correspond to a material loss quantity, due to noise sources affecting the measurement signal. In the work, it is assumed that the actual material loss for a measured value is normally distributed. This assumption has been widely used for estimating the probability of detection. This has also been demonstrated to hold true for diverse NDT methods in a more general derivation.

One way to obtain this distribution is to use calibration specimens. In order for the results to accurately model the range of results expected from inspection of actual in service components, all the relevant variables must be included in the calibration specimens. Construction of calibration specimen is a complex and arduous task. Thus, a section of an actual turbine blade was used as prior knowledge to build the distribution maps.

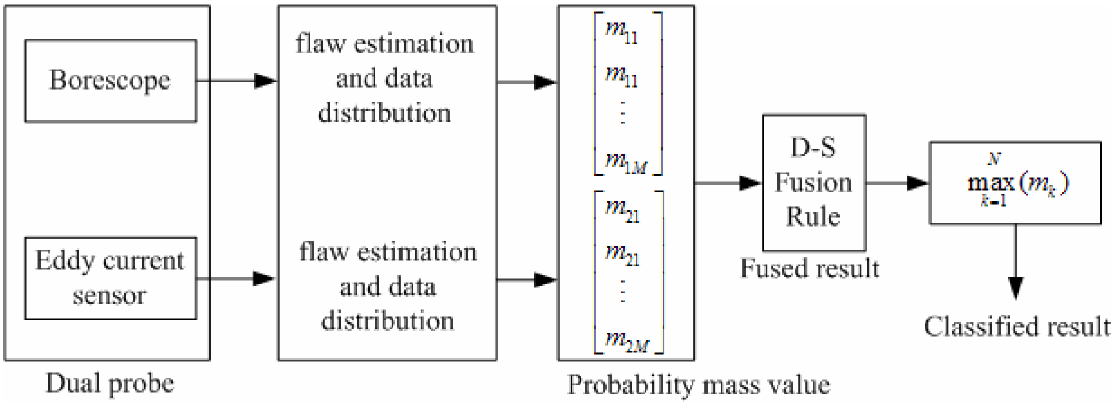


Fig.4 the Procedure to Fuse Borecope and Eddy Current data

**4. Experimental Results**

Cracks and corrosion are primary defects of turbine blade. A turbine blade sample containing machined crack and corrosion was prepared. The dual probe was used to scan the surface of turbine blade sample for defects. The data acquisition and analysis for both probes were done in one computer. According to the procedure to fuse borecope and eddy current data, these two sensors estimate flaw and calculate probability mass value respectively, then fuse result and class result.

In the experiment, the frame of discernment $\theta$ is {crack, corrosion}. Its subset is {{crack}, {corrosion}, {crack, corrosion}}. The element {crack, corrosion} means either crack or corrosion. In fact it means that crack and corrosion can not be distinguished, so it was replaced by {uncertain}. Two inspections were done, and data fusion results were shown in table 1 and table 2 respectively.

In table 1, the crack probability mass value was increased while the uncertain probability mass value was decreased through data fusion. In table 2, the corrosion probability mass value was increased while the uncertain probability mass value was decreased through data fusion. This shows that system uncertainty was decreased and the system discernment to flaws was enhanced using data fusion.

Tab.1 First Inspection Data Fusion Result

| Sensors | Probability mass value | | | Classified result |
|---|---|---|---|---|
| | Crack | Corrosion | Uncertain | |
| Borescope | 0.65 | 0.15 | 0.2 | Crack |
| Eddy current | 0.48 | 0.42 | 0.1 | Uncertain |
| Fusion | 0.7221 | 0.2474 | 0.0305 | Crack |

Tab.2 Second Inspection Data Fusion Result

| Sensors | Probability mass value | | | Classified result |
|---|---|---|---|---|
| | Crack | Corrosion | Uncertain | |
| Borescope | 0.23 | 0.64 | 0.13 | Corrosion |
| Eddy current | 0.38 | 0.45 | 0.17 | Uncertain |
| Fusion | 0.2693 | 0.6969 | 0.0338 | Corrosion |

## 5. Conclusion

The dual probe containing an eddy current probe and borescope to in situ detect defects of turbine blade has been described. Based on the D-S theory of evidence, a decision level data fusion was used to combine probability mass values from borescope and eddy current. The final classification results were obtained by making decisions based on the maximum belief of the fused results. The experimental results show that the high reliable characterization of defect is gained.

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