Design of GMM Damage Alarm Software Based on Embedded Structural Health Monitoring System

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Abstract: Traditional structural health monitoring (SHM) software mainly runs on Windows operating systems, so it has large capacity and needs the support of operating environment. It is hard to transplant the existing SHM software to the embedded SHM system. A type of damage alarm software based on Gaussian mixture model (GMM) migration is designed in C language environment to make it convenient to integrate into the embedded SHM system. The proposed software is verified by the damage monitoring experiment on aircraft lug specimen under varying load, and the results demonstrate that the proposed software can realize effective and reliable structural damage alarm function.

Key words: structural health monitoring; embedded system; Gaussian mixture model(GMM); damage alarm

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0 Introduction

Structural health monitoring (SHM) is a multidisciplinary and comprehensive technology[1-2]. SHM technology can make structural health state assessment and structural remaining life analysis come true. It is wildly applied to the engineering fields, such as aerospace, civil engineering, and large mechanical equipment.

Nowadays, there are many mature SHM system. For example, USA Los Alamos National Laboratory[3] developed an integrated software named "Health of Plate Structures" in the MATLAB environment. It is applied to configuration of signal acquisition hardware system and signal processing software. Acellent Co.[4] developed commercial engineering software, such as SHM Access Pro software and SHM Pact software, in the LabVIEW environment. Their software combined with sensors and hardware system can be utilized in the detection and image of structural damage. Bulletti et al.[5] developed a SHM system for composite pressure vessels and integrated a MATLAB-based user interface software for signal processing and damage localization. Aranguren et al.[6] also developed an integrated damage monitoring software named Human Machine Interface based on LabVIEW, and applied this software to the acquisition and processing of SHM data. Yuan et al.[7-10] developed a piezoelectric guided wave SHM system software based on LabVIEW, which can be used in the monitoring of different types of structural damage, such as crack, corrosion and impact.

Most of the existing SHM software is developed based on LabVIEW and MATLAB, which results in large program volume and low version compatibility. It is also hard to transplant the software into miniaturized SHM systems for aircraft applications[11-12]. Therefore, it is necessary to develop the embedded operating software in C language environment due to its advantages in small and light kernel, high size reduction rate, and fast task execution effi-

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ciency[13-14]. In this paper, the damage alarm software based on Gaussian mixture model (GMM) migration is designed in the C language environment and then is integrated in the embedded SHM system. The proposed software is verified by the damage detection experiment on typical aircraft lug specimen under varying load, and the results demonstrate that the proposed software works normally and realizes reliable and efficient structural damage detection under uncertain conditions.

1 Principle of GMM Damage Alarm Algorithm

The SHM monitoring signals are full of randomness and complexity under the influence of time-varying conditions, so it is a terrific choice to use the GMM modeling method in the damage detection and diagnose process. In the GMM damage alarm algorithm, GMM is utilized for the probability modeling of the signal feature data and the structural damage is alarmed based on the abnormal migration of GMMs[15-17].

1.1 Principle of GMM modeling

GMM is a finite mixed probability model, which can be used to approximate the complex random probability distribution by the weighted combination of multiple Gaussian components without prior knowledge. GMM can be constructed by the expectation maximization (EM) algorithm. In order to reduce the number of iterations and improve the convergence speed of EM algorithm, K-means clustering is used to initialize the Gaussian parameters before the iteration of EM algorithm. The principle of K-means clustering is shown in Fig.1.

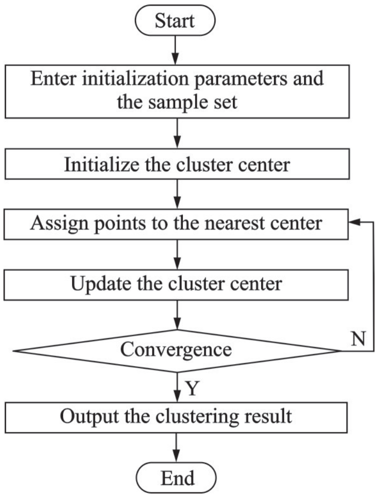


Fig.1 K-means clustering algorithm

Firstly, K-means clustering is performed on obtained SHM data. The initialization calculation of the weight w_k, mean value $\boldsymbol{\mu}_k$ and covariance matrix $\boldsymbol{\Sigma}_k$ of the kth component are defined as follows.

$$w_k = \frac{n_k}{N} \tag{1}$$

$$\boldsymbol{\mu}_k = \boldsymbol{c}_k \tag{2}$$

$$\boldsymbol{\Sigma}_k = \operatorname{cov}(\boldsymbol{X}_k) \tag{3}$$

where n_k is the number of samples in the kth component, N the total number of samples, $\boldsymbol{c}_k$ the kth cluster center, $\boldsymbol{X}_k$ the sample set in the kth cluster, and cov the covariance.

Secondly, the EM algorithm is executed. EM algorithm is an iterative optimization strategy. Each iteration of EM algorithm is divided into expectation step (E step) and maximization step (M step). The steps in the EM algorithm are introduced as follows.

E step:

$$\gamma_{nk}^{\text{new}} = \frac{w_k \phi(\boldsymbol{x}_n | \boldsymbol{\mu}_k, \boldsymbol{\Sigma}_k)}{\sum_{j=1}^{K} w_j \phi(\boldsymbol{x}_n | \boldsymbol{\mu}_k, \boldsymbol{\Sigma}_k)} \gamma_{nk} \tag{4}$$

M step:

$$w_k = \frac{1}{N} \sum_{n=1}^{N} \gamma_{nk}^{\text{new}} \tag{5}$$

$$\boldsymbol{\mu}_k^{\text{new}} = \sum_{n=1}^{N} \gamma_{nk}^{\text{new}} \boldsymbol{x}_n \Big/ \sum_{n=1}^{N} \gamma_{nk}^{\text{new}} \tag{6}$$

$$\boldsymbol{\Sigma}_k^{\text{new}} = \sum_{n=1}^{N} \gamma_{nk}^{\text{new}} (\boldsymbol{x}_n - \boldsymbol{\mu}_k^{\text{new}})(\boldsymbol{x}_n - \boldsymbol{\mu}_k^{\text{new}})^{\mathrm{T}} \Big/ \sum_{n=1}^{N} \gamma_{nk}^{\text{new}} \tag{7}$$

where $\boldsymbol{x}_n$ is the sample data, w_k^{new}, $\boldsymbol{\mu}_k^{\text{new}}$ and $\boldsymbol{\Sigma}_k^{\text{new}}$ are the weight, mean and covariance matrices of the kth Gaussian component after its updating, respectively.

The principle of EM algorithm is shown in Fig.2. After each iteration of E step and M step, the likelihood probability L of the GMM is calculated and the equation of likelihood probability is shown in Eq.(8).

$$L = \sum_{n=1}^{N} \log \sum_{k=1}^{K} w_k \frac{1}{(2\pi)^{\frac{D}{2}} |\boldsymbol{\Sigma}_k|^{\frac{1}{2}}} \mathrm{e}^{-\frac{1}{2}(\boldsymbol{x}_n - \boldsymbol{\mu}_k)^{\mathrm{T}} - \boldsymbol{\Sigma}_k^{-1}(\boldsymbol{x}_n - \boldsymbol{\mu}_k)} \tag{8}$$

where K is the number of omponents. If the updated likelihood probability L^{new} satisfies the inequation

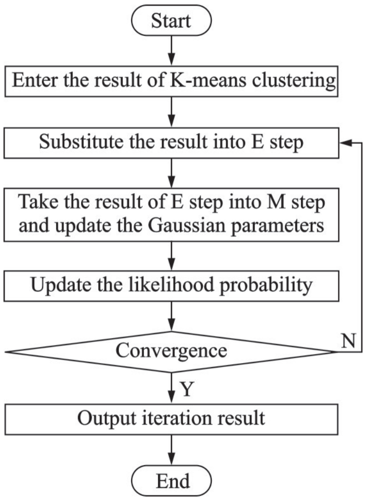


Fig.2 EM algorithm

(9), the iteration will stop. If not, the iteration will continue. In inequation (9), ε is a dimensionless.

$$|L^{\text{new}}/L|-1<\varepsilon \tag{9}$$

1.2 Damage alarm method based on GMM

During the monitoring process, two GMMs are constructed based on the monitoring data. The first GMM is a baseline GMM corresponding to the healthy state and the other is a monitoring GMM corresponding to the damage monitoring state. Once the two GMMs are constructed, the migration or difference between them can be obtained to monitor the damage.

In this paper, the normalized probability of similarity (NPS) is used to measures the migration between two GMMs. The larger NPS is, the larger the difference between baseline GMM and monitoring GMM_k will be. When the NPS value is up to 1, it means that baseline GMM and monitoring GMM_k are completely different. When the structure is irreversibly damaged, the monitoring GMM will completely deviate from the baseline GMM, and the corresponding NPS will increase obviously. Once the NPS exceeds the damage alarm threshold, the software will give damage alarm. The equation of NPS is given as

$$\text{NPS}=1-\frac{\Phi(Z_X|\theta_0)^{\mathrm{T}}\Phi(Z_X|\theta_k)}{\|\Phi(Z_X|\theta_0)\|\cdot\|\Phi(Z_X|\theta_k)\|} \tag{10}$$

where Z_X is the total data sample set, θ_0 the parameter of the baseline GMM including weight w_0, mean $\boldsymbol{\mu}_0$, and covariance matrix $\boldsymbol{\Sigma}_0$, θ_k the parameter of the monitoring GMM_k including weight w_k, mean $\boldsymbol{\mu}_k$, and covariance matrix $\boldsymbol{\Sigma}_k$, $\Phi(Z_X|\theta_0)$ the probability density of Z_X in the baseline GMM, and $\Phi(Z_X|\theta_k)$ the probability density of Z_X in the monitoring GMM_k.

2 Software Development and System Integration

2.1 Software development process

For the development of embedded SHM system, C language has excellent portability and can run in a variety of different architecture of software and hardware platform. Therefore, this paper develops the GMM damage alarm software in C language environment. The software flow is shown in Fig.3. Firstly, the parameter such as the number of components in GMM is initialized. Then, based on the SHM monitoring data, the functional modules including K-means clustering, EM algorithm, NPS calculation and damage alarm are performed in turn. The whole software developed in C language is integrated into the embedded SHM system, which is introduced in the following section.

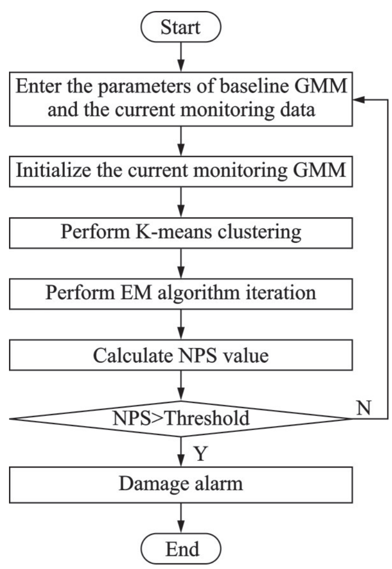


Fig.3 GMM damage alarm software architecture

2.2 Software integration based on embedded SHM system

The integration of GMM damage alarm software into the embedded SHM system is shown in Fig.4, which can be mainly divided into two steps: Application program design and system mirror transplantation. In the step of "application program design", a miniaturized GMM damage alarm software is wrote in C language and the executable application "elf" files are generated. In the step of "system mirror transplantation", the hardware information "hdf" files and executable application "elf" files are packaged to generate the system image files by the PetaLinux tool. When the software is integrated into the embedded SHM system, an executable file named as "image.ub" shown in Fig.5 will be generated in the final integration interface.

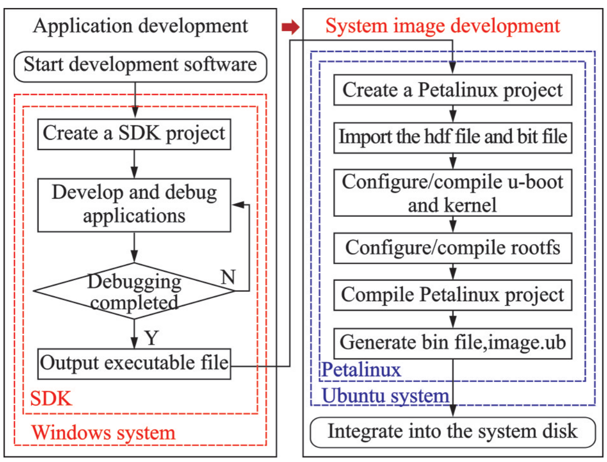


Fig.4 Software development and integration architecture

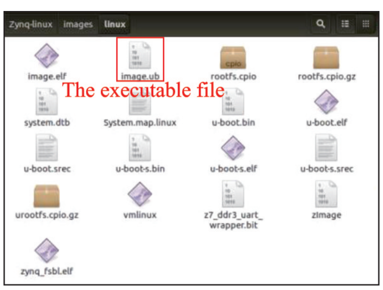


Fig.5 System integration interface

3 Experimental Verification

In this section, the effectiveness and reliability of the GMM damage alarm software are verified by the crack monitoring experiment on the aircraft lug specimen under the influence of varying load. The lug specimen and the corresponding sensor layout are shown in Fig.6. The experimental setup of crack monitoring on lug specimen under varying load is shown in Fig.7. The SUNS890-100 fatigue tensile machine was used to apply fatigue load on the lug specimen, and the real crack growth length was observed by electron microscopy during the monitoring process. During the fatigue test of the lug specimen, the guided wave signals travelling from PZT1 to PZT2 are acquired. Some monitoring signals are shown in Fig.8. Then, these collected monitoring signal are transmitted to the embedded SHM system to verify the damage alarm function of designed C software.

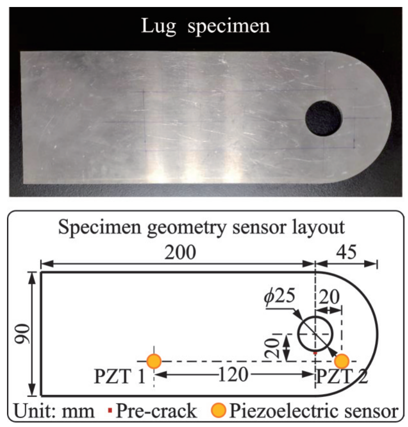


Fig.6 Lug specimen and sensor layout

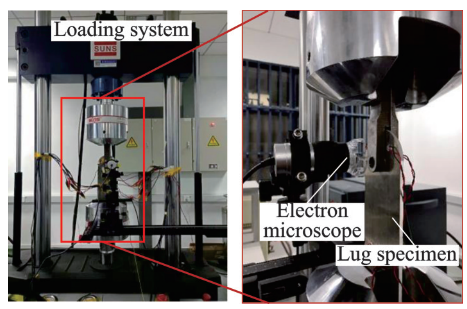


Fig.7 Experimental setup on the lug specimen

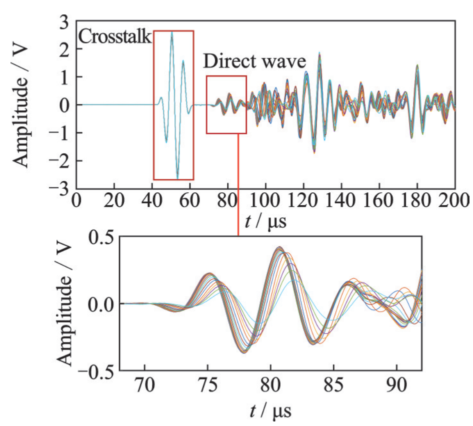
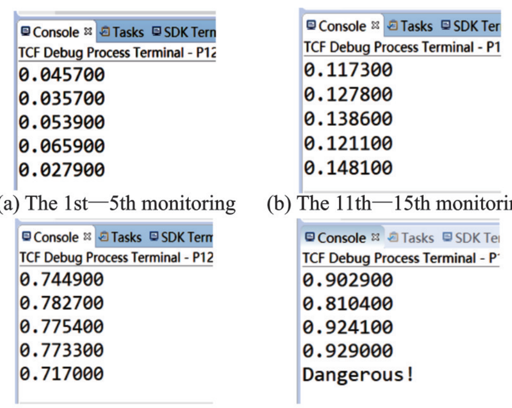


Fig.8 Typical guided wave signals

3.1 Verification of effectiveness

Based on the collected monitoring signals, the GMM damage system software is performed during the monitoring process of the lug specimen under varying load.

During the monitoring process performed by the GMM damage alarm software, some NPS results at typical monitoring times are shown in Fig.9. In addition, Fig.10 shows the damage detection results of GMM damage alarm software on the lug specimen. The damage alarm threshold was set as 0.9. When the GMM software was performed at the 98th monitoring round, the NPS reached the threshold and the software gave the alarm of crack existence. At this alarm time, the actual crack length is about 1 mm as shown in Fig.11. As a result, it can be concluded that the GMM damage alarm software achieved effective alarm function and 1mm crack was detected and alarmed on the lug specimen under the influence of varying load.



(a) The 1st—5th monitoring (b) The 11th—15th monitoring

(c) The 51st—55th monitoring (d) The 96th—100th monitoring

Fig.9 NPS results at different monitoring times

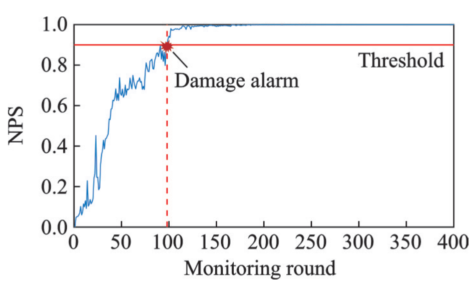


Fig.10 GMM damage alarm software diagnosis results

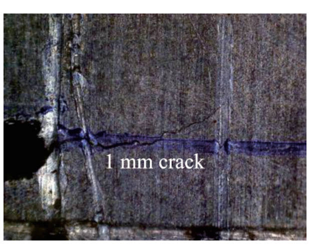


Fig.11 1 mm crack real magnification

3.2 Comparison verification

For comparison, GMM-based damage alarm software developed in the traditional MATLAB environment is also performed based on the same experimental data.

The damage monitoring results of the GMM damage alarm software developed in the C language and MATLAB environments are shown in Fig. 12. It can be seen that the monitoring results of the software developed in C language are basically consistent with that of the software developed in MATLAB. Therefore, the proposed GMM damage alarm software developed in the C language environment realized the damage detection function as reliable as the traditional software developed in the MATLAB environment.

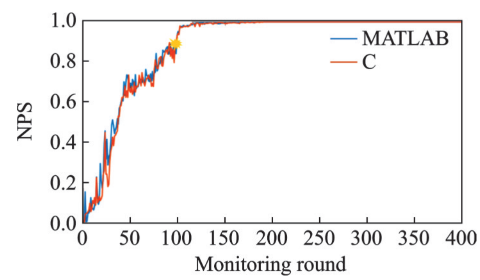


Fig.12 Damage monitoring results of the software in MATLAB and C language environments

The running time of the GMM damage alarm software in C language and traditional MATLAB environments is recorded and present in Table 1. It can be seen that for each time of damage monitoring, C software spent less time than MATLAB software. Therefore, the result indicates that the GMM damage alarm software developed in C language environment achieves a high computational efficiency.

Table 1 Running time of the GMM damage alarm software in MATLAB and C language environments at each time of damage monitoring

Environment	Average time /s	Standard deviation/s
MATLAB	1.51	0.82
C language	0.98	0.36

4 Conclusions

A type of GMM damage alarm software is designed based on C language in order to realize the damage detection function in the embedded SHM system. By using C language, the damage detection function based on the GMM migration is realized in an integrated and portable way. The application results in the crack monitoring on lug specimen illustrate that the designed software realizes the detection of 1 mm crack effectively and reliably under the influence of varying load.

References

[1] YUAN Shenfang. Structural health monitoring[M]. Beijing: National Defense Industry Press, 2007: 33-44. (in Chinese)

[2] STASZEWSKI W J, TOMLINSON G, BOLLER C, et al. Health monitoring of aerospace structures [M]. Chichester: Wiley, 2004.

[3] TIMOTHY G, OVERLY, LAURA D, et al. Developing an integrated software solution for active-sensing SHM[J]. Smart Structures and Systems, 2009, 5 (4): 457-468.

[4] Acellent Company. International website[EB/OL]. [2023-04-30]. http://www.acellent.com.

[5] BULLETTI A, GIANNELLI P, CALZOLAI M, et al. An integrated acousto/ultrasonic structural health monitoring system for composite pressure vessels[J]. IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control, 2016, 63(6): 864-873.

[6] ARANGUREN G, MONJE P M, COKONAJ V, et al. Ultrasonic wave-based structural health monitoring embedded instrument[J]. Review of Scientific Instruments, 2013, 84(12): 29-34.

[7] QIU L, YUAN S F, WANG Q. Development of active structure health monitoring system based on Lamb wave[J]. Piezoelectricity and Acoustooptics, 2009, 31 (5): 763-766.

[8] QIU L, YUAN S F. Development and application of integrated piezoelectric health monitoring and scanning system[J]. Piezoelectricity and Acoustooptics, 2008, 30(1): 39-41.

[9] YUAN S F, MEI H F, QIU L, et al. On a digital wireless impact-monitoring network for large-scale composite structures[J]. Smart Materials and Structures, 2014, 23(8): 75-93.

[10] QIU L, YUAN S F, WANG Q, et al. Design and experiment of PZT network-based structure health monitoring scanning system[J]. Chinese Journal of Aeronautic, 2009, 22(5): 505-512.

[11] YUAN Shenfang, QIU Lei, WU Jian, et al. Challenge in structural health monitoring of large aircraft development[J]. Aeronautical Manufacturing Technology, 2009(22): 62-67. (in Chinese)

[12] MENG S, ALIABADI M. Automation using matrix switch for piezoelectric actuator/sensor based structural health monitoring[J]. Key Engineering Materials, 2015, 627: 213-216.

[13] LIEBIG J, APEL S, LENGAUER C, et al. An analysis of the variability in forty preprocessor-based software product lines[C]//Proceedings of the 32nd ACM/IEEE International Conference on Software Engineering—Volume 1. [S.l.]: IEEE, 2010: 105-114.

[14] PREACHER K J, SELIG J P. Advantages of Monte Carlo confidence intervals for indirect effects[J]. Communication Methods and Measures, 2012, 6(2): 77-98.

[15] QIU L, YUAN S F, CHANG F K, et al. On-line updating Gaussian mixture model for aircraft wing spar damage evaluation under time-varying boundary condition[J]. Smart Materials and Structures, 2014, 23 (12): 125001.

[16] MEI H F, YUAN S F, QIU L, et al. Damage evaluation by a guided wave-hidden Markov model based method[J]. Smart Materials and Structures, 2016, 25 (2): 025021.

[17] QIU L, YUAN S F, BAO Q, et al. Crack propagation monitoring in a full-scale aircraft fatigue test based on guided wave-Gaussian mixture model[J]. Smart Materials and Structures, 2016, 25(5): 055048.

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Author contributions Dr. FANG Fang contributed to methodology, formal analysis, writing and review. Ms. YU Kaixi contributed to software designing, validation and writing-original draft. Prof. QIU Lei contributed to resources, funding acquisition and supervision. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

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基于嵌入式结构健康监测系统的高斯混合模型结构损伤预警软件设计

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摘要：传统结构健康监测软件大多需要Windows操作系统运行环境支持，这种软件很难移植到嵌入式结构健康监测系统上。针对这个问题，在C语言环境下设计了基于高斯混合模型迁移的结构损伤预警软件。在将损伤预警软件集成到嵌入式结构健康监测系统后，通过变化载荷下飞行器典型耳片结构的损伤监测实验对软件监测功能进行了验证。验证结果表明所设计的软件可以在载荷变化下对耳片结构上出现的裂纹进行可靠高效的预警。

关键词：结构健康监测；嵌入式系统；高斯混合模型；损伤预警