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RESEARCH ARTICLE

REVISED A Digital Image Correlation (DIC) prototype system for crack propagation monitoring in aircraft assemblies

[version 2; peer review: 2 approved]

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Abstract

Background: In the Clean Sky 2 project DIMES, the cyclic loading of a section of an A320 wing with pre-existing damage was carried out.
Methods: We present a Digital Image Correlation (DIC) prototype system to monitor crack propagation in the aircraft wing. This system includes a mount for easy installation and adjustment in a confined space.
Results: Strain localization and evaluation due to crack propagation was successfully observed in the Region-of-Interest (ROI) during cyclic fatigue loading. The results from the DIC prototype system were supported by conventional contact Resistance Strain Gauge (RSG) sensors acting as a far-field monitor.
Conclusions: Future improvements, the combination of two DIC modules for a stereo DIC system and the potential of the DIC system for ground-based tests and Structural Health Monitoring (SHM) applications are also discussed.

Keywords

DIC, Structural Health Monitoring, SHM, aircraft, aerospace, fatigue, strain

Open Peer Review

Approval Status ✓ ✓

	1	2
version 2 (revision) 28 Sep 2022		✓ view
version 1 22 Jun 2022	✓ view	? view

1. **Rachel A. Tomlinson**, University of Sheffield, Sheffield, UK

2. **Umberto Galietti**, Politecnico di Bari, Bari, Italy

Any reports and responses or comments on the article can be found at the end of the article.

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Author roles: Luan L: Conceptualization, Data Curation, Investigation, Methodology, Visualization, Writing – Original Draft Preparation; **Crosbie L**: Funding Acquisition, Methodology, Project Administration, Supervision, Writing – Review & Editing; **Michel S**: Methodology, Resources, Writing – Review & Editing; **Hack E**: Supervision, Writing – Original Draft Preparation, Writing – Review & Editing

Competing interests: No competing interests were disclosed.

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REVISED **Amendments from Version 1**

The revised article addresses the comments made by the Reviewers. We have added some information to the cited literature in the Introduction to establish a solid context to embed our study in. We have reworked all the figures by including labels to increase their understandability. We have clarified the idea of the collation of the strain gauge values with the DIC images, Figure 5. We have also stressed, that, in this study, we used the development of strain localization as a qualitative mapping to evaluate the crack propagation, but not quantitative strain evaluation. We have amended the text to clarify that we detect both crack propagation and crack initiation in our data. We have added some technical detail used in the evaluation of the DIC data. Finally, we have provided the videos in mp4 format, in addition to the avi format on Zenodo.

Any further responses from the reviewers can be found at the end of the article

Introduction

Structural Health Monitoring (SHM) refers to continuous monitoring of engineering structures with various sensor systems and the development of a damage detection strategy[1]. SHM systems can ensure increased safety and reliability of aircrafts while reducing maintenance costs[2]. There is an increasing body of research and study of sensor systems with the potential for SHM applications[3–7], including fibre optical systems[8,9]. However, in-flight demonstrations of SHM systems are still rare and mostly limited to fibre optical systems[10]. The DIMES project – Development of Integrated Measurement Systems – aimed at developing an advanced integrated measurement system that has the capability to detect a crack or delamination in a metallic or composite aircraft structure. It is a modular system that accepts diverse sensors such as fibre optics, strain gauges, visual and infrared cameras[11]. Digital Image Correlation (DIC)[12,13] is a camera-based method that analyzes the deformation of a specimen surface by comparing a series of images before and after deformation, which is now widely used for full-field displacement and strain measurement. Compared to conventional contact sensor systems, the DIC method has a number of advantages such as: non-contact optical measurement, convenient installation and full-field deformation analysis, all of which provide great potential for its use in SHM applications. Hoult *et al.*[14] used DIC to measure and characterize cracks in concrete structures. DIC offered a significant advantage over traditional instruments because *a priori* knowledge of the crack locations was not required in the analysis. Sabato *et al.*[15] studied the performance of a 3D-DIC system for railroad tie inspection and ballast support assessment. They found that the high-rate and non-contacting nature of the optical measurement approach led to more frequent and cost-effective measurements, compared to most of the conventional SHM sensing systems such as strain gauges and accelerometers, which are limited due to wires, data transmission, power requirement. Ngeljaratan *et al.*[16] researched the potential of applying DIC systems to the structural vibration behaviour of bridges. They found that very comparable results are obtained from DIC and conventional instrumentation, which showed the potential of DIC to be integrated into larger SHM and condition assessment frameworks.

In this work, the DIC method was used to monitor crack initiation and propagation in an aircraft wing during cyclic fatigue and flight-cycle loading simulating in-flight conditions. A prototype DIC system specially designed for this application is described, which was installed in a section of a wing, and used to monitor several Regions of Interest (RoI). The test results from the prototype DIC system were analyzed and compared with results collected by a remote resistance strain gauge (RSG) sensor for verification of the DIC system. The advantages of the DIC prototype system and its application potential in an in-flight measurement are discussed.

Methods

1. Test setup

In the DIMES project, the cyclic loading of a damaged section of an A320 wing was carried out in the laboratories of Empa. The loading concept was inspired by the typical wing loading in service, e.g. bending in both upward and downward directions. To achieve this loading regime, an asymmetric three-point bending setup was implemented as shown in Figure 1(a). The section of wing was placed upside down approximately 1.25 m above a strong floor. Two pairs of wooden blocks fixed the section of wing at one end. The bending moment was applied via a servo-hydraulic actuator mounted towards the wing tip. The loading force was distributed to two ribs via a fixed frame. The front spar of the wing, shown in Figure 1 (b), contained a pre-existing crack which was defined as the RoI. The DIC system was installed into the wing box through an access hole as highlighted in Figure 1(a). The inside surface of the front spar was monitored for the detection of any crack propagation during the cyclic loading of the section of wing. Conventional contact sensors such as resistance strain gauges (RSG) and Fiber Bragg Gratings (FBG) were installed on the wing section. The strain value of one RSG installed on the outside surface of the front spar towards the clamp was used for comparison with the DIC test results.

2. Design and installation of prototype DIC system

A prototype system was designed for this application as shown in Figure 2 (a). The prototype consisted of a VC MIPI IMX296 camera (1440 × 1080 pixels, pixel size 3.45 µm, Vision Components, Ettlingen, Germany), a 5 mm C-Mount Computar lens H0514MP2 and a Raspberry Pi 3B+ (Raspberry Pi Foundation, Cambridge, UK) mounted on a 3D-printed frame with a footprint of 90 mm × 170 mm. The 3D-printed frame was connected to an articulated arm of length 200 mm S-20 FISSO (Baitella AG, Zurich, Switzerland) that had three joints to adjust the viewing angle and working distance of the DIC system relative to the surface of the RoI. The other end of the articulated arm was fixed to a slotted aluminum plate, which in turn was fixed via two Studs from a click bond (Click bond Inc, Carson City, USA) on flat surfaces inside the wing bay. An LED ring (Adafruit Industries, New York, USA) was installed around the lens for illumination in the confined space. The weight of the DIC module, without the cable

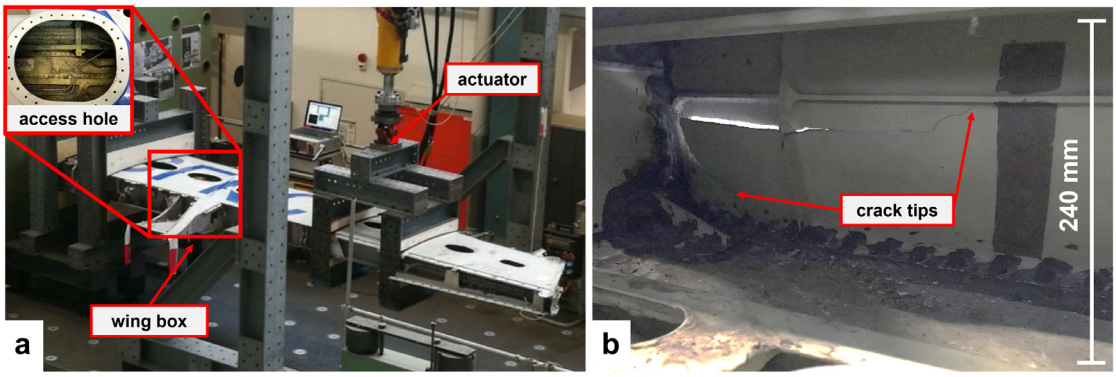


Figure 1. Test setup for the wing section: (**a**) load frame installed on a strong floor at Empa with an access hole used for installation of the DIC system into the wing box; (**b**) front spar surface with pre-existing cracks viewed from inside of the wing box.

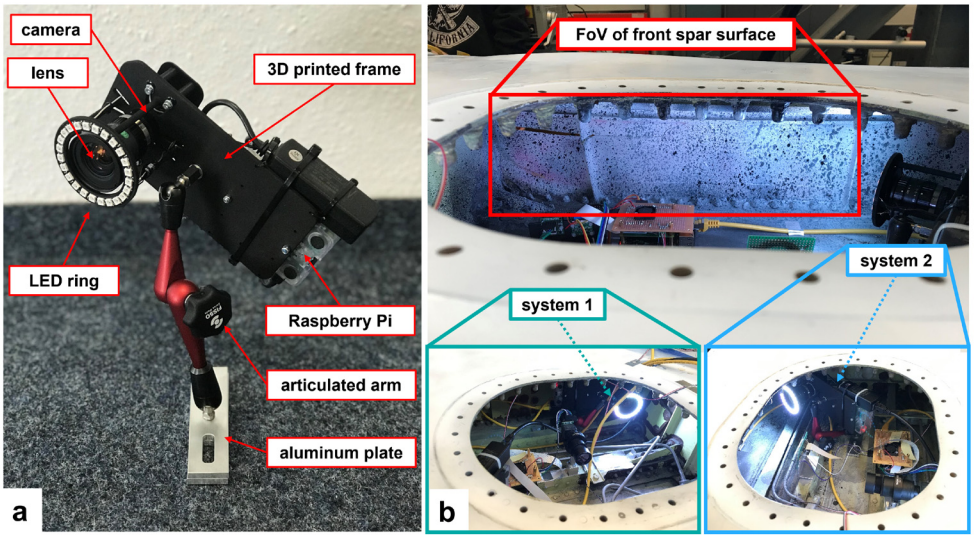


Figure 2. (**a**) the prototype DIC system with its ring LED. (**b**) the installation of DIC system 1 perpendicular to the front spar surface and DIC system 2 with an oblique viewing angle. Other components inside the wing box belong to different measurement systems, which are not discussed here.

connections, was less than 750 g. The DIC system was connected to a Network Attached Storage (NAS), where all recorded images were stored together with data from other sensor systems. Post-processing was used for DIC data evaluation, which means that the full-field DIC results were analyzed after the cyclic loading test and subsequently compared with data from a RSG installed on the front spar to verify the performance of the prototype DIC system.

Spray paint was used to prepare a speckle pattern on the front spar due to its flexible application in the confined space of the wing box. White matte color was first painted as background and black matte color was then sprayed to generate speckle patterns on the front spar surface. Two of the prototype DIC systems were installed in the wing to monitor the same surface area of the front spar as shown in Figure 2 (b). DIC system 1 was aligned perpendicular to the front spar surface and system 2 was installed with an oblique viewing angle. Based on a working distance of approximately 400 mm, a Field-of-View (FoV) of 400 mm × 300 mm was achieved, which allowed the whole of the pre-existing cracks on the front spar to be viewed (see highlighted boxes in Figure 3). One crack tip was located in the left corner of the front spar and the other crack was close to a stringer in the right part of the FoV. After the installation of both DIC systems, the access hole was covered and the LED rings provided sufficient lighting for the DIC measurements.

3. Test method

A cyclic loading test was carried out on the section of wing with a deflection of -80 mm to the fixed wing end and

an amplitude of 15 mm at 1.25 Hz via the servo-hydraulic actuator. The image acquisition rate of both DIC systems was set to 0.067 Hz (one image every 15 seconds). The cyclic loading test lasted for around 25 hours and both DIC systems acquired more than 6000 images during the test. The loading direction is indicated in Figure 3. After the cyclic loading test, post-processing of the recorded images from both DIC systems was performed with a facet size of 25×25 pixels and a grid spacing of 10 pixels using Istra4D, Dantec Dynamics' DIC software. The distribution and magnitude of the maximum principal strain, ε_1, which represents the largest tensile deformation on the front spar surface, was analyzed with a focus on the crack tips, to study the crack propagation during the cyclic loading test.

Results and discussion

In this study, we used the development of strain localization as a qualitative mapping to evaluate the crack propagation process. Hence, no quantitative strain evaluation and analysis was included. Figure 4 shows the distribution of the (pseudo) maximum principal strain, ε_1 from both DIC systems at various time steps[17].

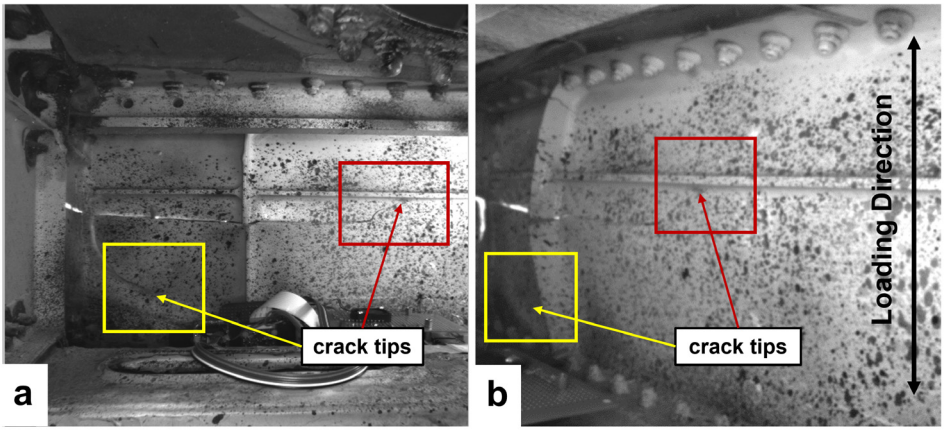


Figure 3. FoV of DIC system 1 (**a**) and DIC system 2 (**b**) containing two crack tips.

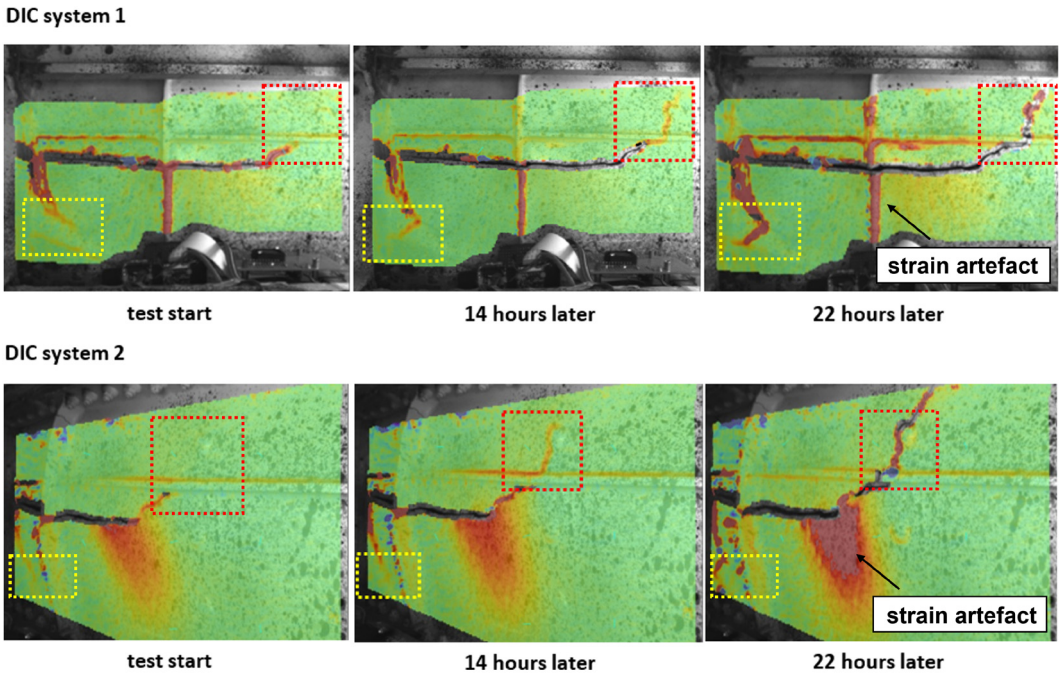


Figure 4. The distribution of the maximum principal strain, ε_1 from both DIC systems at various time steps. Crack propagation was detected in the red box, while crack initiation occurred in the yellow box. It grew perpendicular to the orientation of the existing crack. Note that strain artefacts are highlighted with arrows.

Strain localization was observed around both crack tips in the highlighted boxes shown in Figure 4 at the beginning of the cyclic loading test. After 14 hours, growth of the strain localization was simultaneously observed in both highlighted boxes. After 22 hours, crack propagation of both crack tips on the front spar of the wing was confirmed. Decorrelation of DIC data around the crack tip in the red frame highlighted in Figure 4 was observed due to the crack opening. Other areas of strain localization, highlighted in Figure 4 with arrows, were considered to be strain artefacts, such as at the edge of the correlation area or along lines of structural reinforcement. A large area of strain localization was observed in the middle of the FoV of DIC system 2 in Figure 4, where strain increased during the test. Meanwhile, no strain localization in the same area was detected by DIC system 1, which suggested the strain localization observed in DIC system 2 was also an artefact. It was caused by the out-of-plane motion of the front spar during the cyclic loading test. Sutton *et al.*[18] found that out-of-plane motion can introduce displacement gradients in the image plane and results in strain artefacts. Using two DIC systems with different viewing angles to monitor the same region of interest made it possible to identify the influence of out-of-plane motion on the 2D-DIC results. However, the absolute strain value cannot be accurately determined due to the inevitable out-of-plane motion. Therefore, for damage monitoring in this study, we focussed on relative changes in the strain field instead of quantitative strain analysis. Stereoscopic DIC measurement was not considered, as the fields of view and focus changed during the fatigue cycle, and the two DIC systems were mounted independently from each other. However, combining two 2D-DIC systems into a stereo system on a rigid mount is straightforward.

The RSG installed on the front spar towards the clamp, Figure 5(b) served as a far-field strain monitor of damage propagation. Decreasing levels of compressive strain indicate a strain relieve around the strain gauge, caused by the propagating damage, but it cannot tell the location where this occurs. The DIC results for the strain distribution around the crack tip locate the propagating damage, and therefore they were compared with the results from the RSG at four time steps in Figure 5(a).

The upper part of Figure 5(a) shows the strain evaluation at the crack tip at different time steps in the red highlighted box from DIC system 1 in Figure 4. The bottom part of Figure 5(a) shows the strain value over time measured from the RSG. The RSG signal was captured with a frequency of 7 Hz and was averaged in this graph by 256-value rolling mean to reduce the influence of the cyclic wing deflection on the strain value caused by the fatigue load. During the first hours after the start of the various tests, there was no significant change in the RSG signal or the DIC strain distribution. The crack tip was observed close to the stringer as highlighted in Figure 5(a) with an arrow. A similar strain localization around the crack tip can be observed in strain map at the start of the experiment shown in Figure 4 (DIC system 1). Between 14 and 18 hours, the area of high strain moved from the crack tip across the stringer suggesting crack propagation had begun. Meanwhile, the RSG showed increasing compressive strain. This process continued, and from 22 hours onward, the crack across the stringer was visible and propagated out of the FoV to the top right, while the compressive strain value of the RSG kept increasing. Based on the correlation between data from DIC and RSG, we found that the prototype DIC system exhibited an excellent

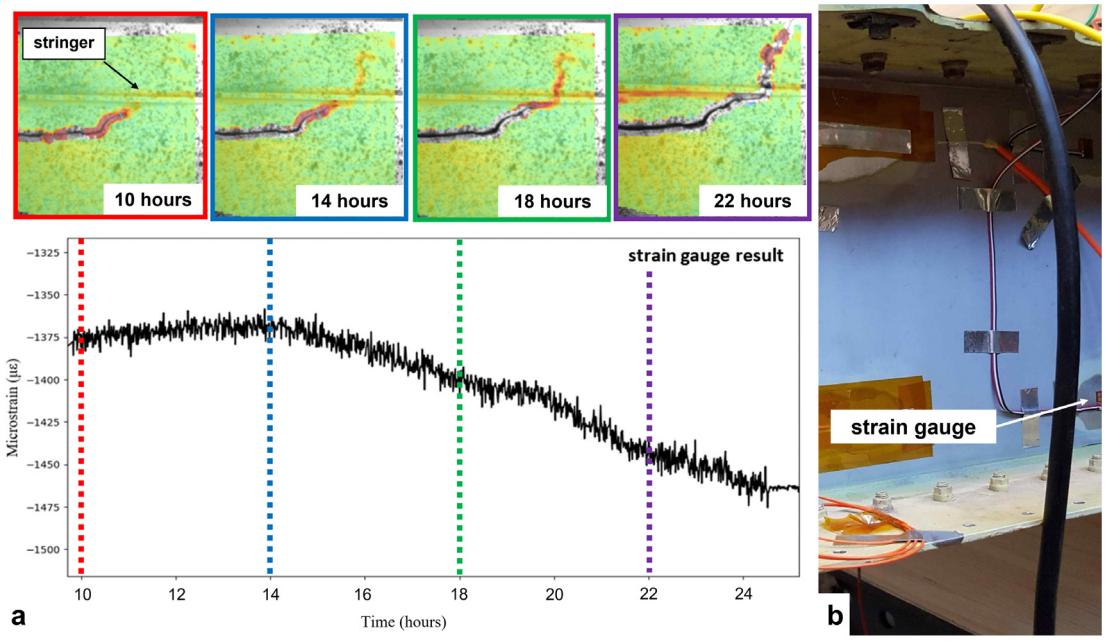


Figure 5. (**a**) Strain signal measured from a RSG sensor installed on the front spar collated with DIC results at various points in time. (**b**) Position of the strain gauge close to the wooden block used for clamping the wing box.

performance for damage detection and stability in tests over long times. In addition to the onset of damage propagation, the full-field deformation maps from DIC provided information about the location of the damage in a defined RoI. The adaptable mounting would allow this FoV to be changed for either following the crack tip further, or for pointing at other locations where crack initiation was expected.

Nevertheless, there are multiple opportunities for optimization of the prototype DIC system for potential SHM applications. One major downside of the DIC measurements is the relative large volume of data generated, i.e., the images acquired from the cameras. Here, we used 1.5 MB for one image, which added up to 17 GB of data over 24 hours with two systems. One option for data reduction is to use signals from other sensor systems to trigger fast image acquisition by the DIC system for more detailed damage monitoring only when an indication of damage growth is found, while a low image acquisition rate is used otherwise. Based on this method, it would be possible to achieve reduced data volumes and yet still obtain the possibility for detailed analysis of damage evaluation.

Post-processing of recorded images was used in this study, which means there was no real-time feedback for automatic damage detection in the wing from the DIC system. For long-term continuous SHM applications, a real-time measurement capability for the DIC system would be particularly important in order to gain the latest status of the structure. However, automatic damage detection is challenging due to the complexity of damage definition, i.e, the type of damage, the location of damage, and the critical level of damage.

The DIC prototype system tested in this study is a 2D-DIC system, which means strain artefacts caused by out-of-plane deformation are unavoidable. This will raise the risk that accurate information cannot be identified from the artefacts. The development of a 3D-DIC system for this application could solve this problem. The shape and displacement of the specimen surface could be determined so that artefacts could be eliminated[19]. But there are multiple challenges, such as system calibration in a confined space, the requirement for system stability to maintain a fixed relative position between the two cameras. It would also add weight to the system, which is unwanted in many SHM applications.

Conclusions

In this work, we have designed a prototype DIC system for crack propagation monitoring in an aircraft wing. Two DIC systems were installed in a wing box and both DIC systems successfully provided data fields that illustrated crack propagation using post-processing after a cyclic loading test. Test results from the DIC systems and an RSG showed consistency with each other during crack propagation. Influence of strain artefacts caused by out-of-plane motion and the optimization of the prototype DIC system have been discussed. A full-field DIC prototype system could provide more detailed damage analysis, such as determination of the location and type of damage, and has potential in SHM applications.

Data availability

Underlying data

Zenodo: DIC images for DIMES paper, https://doi.org/10.5281/zenodo.7082028

This project contains the following underlying data[17]:

- DIC_System_1_0_hours.bmp
- DIC_System_1_14_hours_later.bmp
- DIC_System_1_22_hours_later.bmp
- DIC_System_2_0_hours.bmp
- DIC_System_2_14_hours_later.bmp
- DIC_System_2_22_hours_later.bmp
- Video_DIC_System_1_EngPrinpicalStrain1.avi
- Video_DIC_System_2_EngPrincipalStrain2.avi

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

Acknowledgements

We thank Eann Patterson from University of Liverpool for coordinating the DIMES project and for his thorough comments on the manuscript; Peter Lambert and Ceri Middleton from University of Liverpool for collaboration on the project; Richard John Greene from Strain Solutions Ltd. for application of the strain gauges. We thank the Topic Manager, Linden Harris from Airbus SA, for providing the wing box and Walter Bollier, Empa, for running the fatigue tests.

This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 820951. The opinions expressed in this paper reflect only the authors' view, and the Clean Sky 2 Joint Undertaking is not responsible for any use that may be made of the information it contains.

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Version 2

Reviewer Report 03 October 2022

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✔

Umberto Galietti
Department of Mechanics Mathematics and Management (DMMM), Politecnico di Bari, Bari, Italy

The most important suggestions were well considered and the amended version is fully approved. Excellent piece of work.

Hopefully there will be chance for the authors in future works to perform a sensitivity analysis and a comparison with other techniques.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Experimental Stress Analysis; Materials characterization including Fracture Mechanics and Fatigue ; Non Destructive Testing; Infrared Thermography applications.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 18 August 2022

https://doi.org/10.21956/openreseurope.15765.r29584

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Umberto Galietti
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Department of Mechanics Mathematics and Management (DMMM), Politecnico di Bari, Bari, Italy
[2] Department of Mechanics Mathematics and Management (DMMM), Politecnico di Bari, Bari, Italy

This is a very nice application of DIC for SHM.

For the aim of the work, that is showing the feasibility of DIC on a confined volume during a fatigue test, literature provided is a sufficient state of the art. I would suggest anyway to insert some info and citation of the competing SHM systems to enhance to analysis of the system for SHM.

The declared aim of the prototype is partly demonstrated, being the cracks identified already well grown at the beginning of the test. The capability to identify the start of the crack has still to be experimentally showed. Even if I agree that the system shows enough sensitivity to do it, the demonstration of the capability to identify crack just initiated would increase significantly the advantage of the system for SHM. In fact the SG results already provide info about the occurring damage after 14 hours testing and, if the advantage of the DIC is to provide the info of the damage at an early stage, at least an estimation of the smallest crack for each setup that can be identified should be provided and it can greatly increase the appeal for the use of the prototype.

In order to enhance the replicability of the test, even if a commercial software was used for this work, I strongly suggest to provide info about the DIC analysis parameters.
I could not open the *.avi files provided in the repository. For sure it is just because of the programmes that I do not have on the PC, but I suggest anyway to indicate a suitable program to open them.

For future work a comparison with other cited techniques and a sensitivity analysis would greatly enhance vantages and disadvantage for SHM competing techniques.
Thanks for the very nice application.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Experimental Stress Analysis; Materials characterization including Fracture Mechanics and Fatigue ; Non Destructive Testing; Infrared Thermography applications.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 14 Sep 2022

Erwin Hack

This is a very nice application of DIC for SHM.

Thank you for your positive rating

For the aim of the work, that is showing the feasibility of DIC on a confined volume during a fatigue test, literature provided is a sufficient state of the art. I would suggest anyway to insert some info and citation of the competing SHM systems to enhance to analysis of the system for SHM.

We have added some information to the cited literature [14-16] in the Introduction.

The declared aim of the prototype is partly demonstrated, being the cracks identified already well grown at the beginning of the test. The capability to identify the start of the crack has still to be experimentally showed. Even if I agree that the system shows enough sensitivity to do it, the demonstration of the capability to identify crack just initiated would increase significantly the advantage of the system for SHM.

We have amended the text to clarify that in Fig. 4 we see both crack propagation (red box), as well as crack initiation (yellow box).

In fact the SG results already provide info about the occurring damage after 14 hours testing and, if the advantage of the DIC is to provide the info of the damage at an early stage, at least an estimation of the smallest crack for each setup that can be identified should be provided and it can greatly increase the appeal for the use of the prototype.

Thank you for your suggestion. We agree that, for a practitioner, the minimum detectable crack length is a desirable measure. However, it was not possible to relate the strain concentration to a crack length.

In order to enhance the replicability of the test, even if a commercial software was used for this work, I strongly suggest to provide info about the DIC analysis parameters.

We have added "with a facet size of 25×25 pixels and a grid spacing of 10 pixels" at the appropriate location.

I could not open the *.avi files provided in the repository. For sure it is just because of the programmes that I do not have on the PC, but I suggest anyway to indicate a suitable program to open them.

We are sorry that you could not play the videos. We now provide both videos also in .mp4 format through the repository.

For future work a comparison with other cited techniques and a sensitivity analysis would greatly enhance vantages and disadvantage for SHM competing techniques. Thanks for the very nice application.

Thank you for this suggestion. However, we feel that it is beyond the scope of the present paper, as we wanted to demonstrate the potential of the DIC prototype.

Competing Interests: No competing interests were disclosed.

Reviewer Report 08 August 2022

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This paper is a well-written account of small, lightweight DIC system which is shown to be effective in an enclosed area such as inside an aircraft wing box for structural health monitoring. The authors describe the new system and present the results of a test which demonstrates its capabilities and limitations.

I recommend a number of changes to the paper which will clarify what was done to the reader and correct minor errors.

Introduction:

In the introduction the authors state that “in-flight demonstrations of SHM systems are still rare and mostly limited to fibre optical systems” but don’t specifically say that the work presented here (part of the DIMES project) is novel because it can be used in-flight. I think adding this emphasis would highlight the novelty of the work.

Figures

Including photographs of experimental apparatus in papers is always tricky because the authors know exactly what the picture represents, but sometimes forget that the reader does not. All the figures would benefit from some sort of scale indicator and labels on the salient features.

Figure 1: a) label the wing box, the actuator, the access hole, b) pre-existing cracks. Figure 2: a) label all the features mentioned in the text b) it is really difficult to understand what I'm looking at here- there appears to be other cameras in the image in addition to the DIC?

It is not clear exactly where the strain gauge is located that is used in Figure 5. Please add a label on one of the images of the apparatus. It is also not clear how the data from this strain gauge compares to the DIC results. Clarification of what you are comparing and why is needed.

Figure 3: it's not easy to see the dotted boxes or cracks (I printed the paper in black and white to read it- then had to resort to downloading and enlarging the figures because I couldn't see the cracks). Suggest you make the boxes white not red and point the arrow actually at the crack tip and not just the box.

Figures 4 and 5 are maps of principal strain but have no quantitative colour scale. I understand why this is the case, but the reasons should be clearer. I think you need to clarify at the very start of the Results and Discussion section that you are using the strain as a damage mapping technique and not as a quantitative strain technique. Then go on to say you know you have out of plane strain which is causing the spurious strain artefacts, but it will also cause errors in the quantitative 2D strains. You quite rightly say that 3D DIC will be complicated to implement and calibrate in a small space and I honestly think that using 2D DIC works well as a damage tracking method. In addition to a clarification at the start of the Results section, I suggest that after the sentence "Therefore, for damage monitoring, we focussed on relative changes in the strain field in this study" you could add that for this reason there are no quantitative scales in the data images.

The narrative around Figure 5 is a little confusing. You state that "During the first 10 hours after the start of the experiment, there was no significant change in the RSG signal or the DIC strain distribution" but you don't actually present these data. I suggest including the data from just after the start of the test to support this statement.
Replace "After 14 hours" with "Between 14 and 18 hours".

You say "Based on the comparison between data from DIC and RSG, we found that the prototype DIC system exhibited an excellent performance and stability in tests over long time periods for damage detection." I can accept the stability claim, but what in the comparison indicates "excellent performance"? This is too vague, and you could be ore specific in your claims. It would help if you made it clear (as stated above) exactly what you are comparing and why. Are you basically saying that the DIC data shows the cracks growing and the magnitude strain increasing, and the RSG shows strain increasing too? The cynic would then say that you don't need the complication of DIC. So I think you can emphasise more strongly that, while the RSG gives the same indication of increasing damage through the strain magnitude increase, that (superior to RSG) the DIC allows location detection also. Just the addition of a couple of words here would emphasise the advantages of DIC for this sort of work. Also please be consistent with terminology – suggest you refer only to "increasing compressive strain" and don't then talk about decreasing strain.

Final line of Results and discussion section: never start a sentence with “And”.

I think the above recommendations would give the paper polish and make it easier to understand.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Experimental Mechanics, DIC, strain measurement

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 14 Sep 2022

Erwin Hack

This paper is a well-written account of small, lightweight DIC system which is shown to be effective in an enclosed area such as inside an aircraft wing box for structural health monitoring.

Thank you for your overall positive rating.

Introduction:

In the introduction the authors state that “in-flight demonstrations of SHM systems are still rare and mostly limited to fibre optical systems” but don’t specifically say that the work presented here (part of the DIMES project) is novel because it can be used in-flight. I think adding this emphasis would highlight the novelty of the work.

We have added a phrase in the Introduction to highlight that the work is for

simulating in-flight conditions, and that it has advantages compared to FBG.

Figures

Including photographs of experimental apparatus in papers is always tricky because the authors know exactly what the picture represents, but sometimes forget that the reader does not. All the figures would benefit from some sort of scale indicator and labels on the salient features.

Figure 1: a) label the wing box, the actuator, the access hole, b) pre-existing cracks. We have added labels to the main parts of the test set-up in Fig.1, as well as a scale bar inside the wing box.

The figure caption has been updated.

Figure 2: a) label all the features mentioned in the text b) it is really difficult to understand what I'm looking at here- there appears to be other cameras in the image in addition to the DIC?

We have added labels to the main parts of the test set-up in Fig.2 and have highlighted the DIC systems. The caption has been updated.

It is not clear exactly where the strain gauge is located that is used in Figure 5. Please add a label on one of the images of the apparatus. It is also not clear how the data from this strain gauge compares to the DIC results. Clarification of what you are comparing and why is needed.

The RSG in question is located on the front spar towards the clamp of the wing. This location is not visible on any of the figures so far, but we added a photo to Fig. 5. We have added a sentence to clarify the idea of the comparison of the strain values with the DIC images. The caption of Fig 5 was adapted accordingly.

Figure 3: it's not easy to see the dotted boxes or cracks (I printed the paper in black and white to read it- then had to resort to downloading and enlarging the figures because I couldn't see the cracks). Suggest you make the boxes white not red and point the arrow actually at the crack tip and not just the box

We have optimized Fig. 3 with full lines and different colours, so that the boxes and arrows are better visible in both colour and gray print. The arrows point directly on the crack tips.

Figures 4 and 5 are maps of principal strain but have no quantitative colour scale. I understand why this is the case, but the reasons should be clearer. I think you need to clarify at the very start of the Results and Discussion section that you are using the strain as a damage mapping technique and not as a quantitative strain technique. Then go on to say you know you have out of plane strain which is causing the spurious strain artefacts, but it will also cause errors in the quantitative 2D strains. You quite rightly say that 3D DIC will be

complicated to implement and calibrate in a small space and I honestly think that using 2D DIC works well as a damage tracking method. In addition to a clarification at the start of the Results section, I suggest that after the sentence “Therefore, for damage monitoring, we focussed on relative changes in the strain field in this study” you could add that for this reason there are no quantitative scales in the data images.

Thank you for your suggestion. The following sentences at the beginning of Results and Discussion and further down were added: “In this study, we use the development of strain localization as a qualitative mapping to evaluate the crack propagation process. Hence, no quantitative strain evaluation and analysis is included.” “Therefore, for damage monitoring in this study, we focused on relative changes in the strain field instead of quantitative strain analysis.”

The narrative around Figure 5 is a little confusing. You state that “During the first 10 hours after the start of the experiment, there was no significant change in the RSG signal or the DIC strain distribution” but you don’t actually present these data. I suggest including the data from just after the start of the test to support this statement.

We have shown the strain distribution at test start in Figure 4 – DIC system 1, which shows a similar strain distribution compared to the test result after 10 hours. We added the following sentence: “A similar strain localization around the crack tip can be observed in strain map at the start of the experiment shown in Figure 4 (DIC system 1).

"Replace “After 14 hours” with “Between 14 and 18 hours”. **We have implemented this change to the text.**

You say “Based on the comparison between data from DIC and RSG, we found that the prototype DIC system exhibited an excellent performance and stability in tests over long time periods for damage detection.” I can accept the stability claim, but what in the comparison indicates “excellent performance”? This is too vague, and you could be ore specific in your claims. It would help if you made it clear (as stated above) exactly what you are comparing and why. Are you basically saying that the DIC data shows the cracks growing and the magnitude strain increasing, and the RSG shows strain increasing too? The cynic would then say that you don’t need the complication of DIC. So I think you can emphasise more strongly that, while the RSG gives the same indication of increasing damage through the strain magnitude increase, that (superior to RSG) the DIC allows location detection also. Just the addition of a couple of words here would emphasise the advantages of DIC for this sort of work.

We have rephrased the text as follows: Based on the correlation between data from DIC and RSG, we found that the prototype DIC system exhibited an excellent performance for damage detection and stability in tests over long times. In addition to the onset of damage propagation, the full-field deformation maps from DIC provide information about the location of the damage in a defined RoI.

Also please be consistent with terminology – suggest you refer only to “increasing

compressive strain" and don't then talk about decreasing strain.

We have implemented this change to the text.

Final line of Results and discussion section: never start a sentence with "And".

We have rephrased the sentence.

Competing Interests: No competing interests were disclosed.