

Large-Scale Digital Image Correlation for Aeronautical Structures with Complex Geometry: End-to-end Workflow and Validation on an Engine Nacelle

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Abstract

Digital Image Correlation (DIC) provides dense displacement fields and, by spatial differentiation, strain fields, and has become a mature, widely documented optical measurement technique for experimental mechanics and structural testing [1, 2, 3, 4]. While its performance is well established in controlled laboratory conditions, transferring DIC to full-scale aeronautical components remains challenging because scaling up the field of view and the structural size amplifies non-idealities: strong 3D curvature and occlusions, constrained camera placement, time-varying outdoor illumination, large data volumes, and the need for defensible uncertainty and confidence metrics.

Large-scale, non-intrusive deployments have nevertheless demonstrated feasibility in flight-test contexts using Image Pattern Correlation Technique (IPCT), including wing deformation measurements on transport aircraft and related campaigns [5, 6, 7]. Reported in-flight measurement workflows highlight practical issues that become critical at scale (reference-frame definition, operational constraints, stability of calibration), while achieving sub-millimetric displacement accuracy in representative configurations (e.g., order 0.2 mm in an in-flight wing deformation context) [7].

This contribution targets the next step: robust DIC on complex, highly curved aeronautical structures, using a deformed engine nacelle as a case study. We present an end-to-end workflow covering (i) speckle design and application rules adapted to curvature and multi-material surfaces, guided by established criteria for speckle quality and its impact on correlation uncertainty [8, 9, 10]; (ii) camera-network calibration and operational revalidation under constrained test environments, leveraging standard calibration formalisms and practical recommendations [11, 12]; (iii) radiometric robustness to sunlight transients and mixed illumination, using correlation formulations and processing safeguards designed to mitigate intensity changes [13, 14, 15, 16]; (iv) computational scaling strategies for large image sets, including distributed/accelerated approaches consistent with global/integrated DIC formulations [17, 19]; and (v) validation of displacement/strain outputs through uncertainty quantification and confidence indices grounded in error-assessment methodologies and good-practice guidance [20, 21, 22], complemented by cross-checks with independent sensors when available.

Using a global DIC approach implemented in EikoTwinDIC, we discuss how geometry-aware process-

ing and metrology-oriented validation can increase robustness on complex shapes while remaining compatible with industrial test constraints. Finally, we outline a perspective toward continuous self-calibration through sensor fusion, in particular combining DIC with embedded strain gauges to monitor calibration drift and improve confidence over long-duration campaigns.

Keywords: Digital Image Correlation; large-scale testing; aeronautics; complex geometry; calibration; illumination robustness; uncertainty; global DIC; sensor fusion.

1 Introduction

Digital Image Correlation (DIC) is now a standard full-field optical technique for displacement measurement in experimental mechanics. In its most common form, a textured surface is observed in a reference state and in one or several deformed states, and the apparent motion of the texture is estimated to recover the displacement field [1, 2, 3]. Stereo configurations extend this principle to three-dimensional surface kinematics, while global or finite-element-based formulations allow the displacement field to be represented directly on a mechanical discretization [17, 18].

The method is mature in laboratory conditions. Its transfer to full-scale aeronautical structures is far less trivial. When the field of view grows from coupons or subcomponents to an aircraft structure, the difficulty is not only geometric scaling. The whole measurement chain becomes more fragile: the observed surface is highly curved, optical access is constrained by the aircraft architecture, illumination is no longer controlled, calibration must remain valid under operational conditions, image sequences become large, and useful observables must be distinguished from visually plausible but poorly defensible outputs. Large-scale DIC should therefore not be regarded as a simple extrapolation of laboratory DIC, but as a coupled instrumentation and metrology problem [23].

This issue is increasingly relevant for flight-test applications, where non-intrusive full-field kinematic measurements are sought on structures whose deformation cannot be adequately described from sparse sensors alone. Previous optical flight-test campaigns, in particular those based on Image Pattern Correlation Technique (IPCT), have shown that transport-aircraft deformation measurements are feasible in representative operating conditions [5, 6, 7]. Those works also made clear that robustness at scale depends on the full measurement

chain rather than on the correlation algorithm alone.

The present work addresses that next step for a complex aeronautical surface, namely a deformed engine nacelle observed from cameras installed inside the aircraft cabin. The objective is not to introduce a single isolated algorithmic improvement, but to describe an end-to-end workflow covering the full chain from pattern design to validation. The central idea of the paper is that robust full-field optical measurement on such structures requires a coupled treatment of geometry, radiometry, calibration, processing scalability, and confidence assessment.

2 Measurement context and targeted observable

The case study considered in this work concerns a deformed engine nacelle observed from the aircraft cabin. The practical engineering objective is to monitor relative displacements over a representative footprint in order to support structural interpretation and interface assessment. Compared with sparse contact instrumentation, DIC offers the decisive advantage of a spatially dense kinematic description over the observed surface.

The application is particularly demanding. The nacelle is not a flat or weakly curved object. It combines strong three-dimensional curvature, multi-panel geometry, local protruding features, and partial self-occlusions. The available viewpoints are not chosen from ideal photogrammetric criteria but from the positions that remain accessible in the aircraft. The result is a non-uniform observation geometry with distance variation, grazing incidence in some zones, and local masking in others. In addition, observation is performed through cabin windows and under outdoor illumination, which introduces radiometric perturbations that would be secondary in a controlled laboratory setup.

A second point must be stated explicitly. In the present work, the primary observable is the displacement field itself. Although strain may in principle be derived from the measured displacement field, its local reliability is substantially more sensitive to radiometric defects, calibration drift, spatial-resolution heterogeneity, and regularization effects. The paper is therefore written from the standpoint of robust displacement-field measurement and validation. The actual observed footprint and the global illumination conditions are shown in Fig. 1.

3 Main challenges of large-scale in-flight DIC

3.1 Complex geometry and viewpoint constraints

Large aeronautical surfaces differ from laboratory specimens not only by size, but by the geometry of observation. Apparent feature size varies with camera-to-surface distance and local

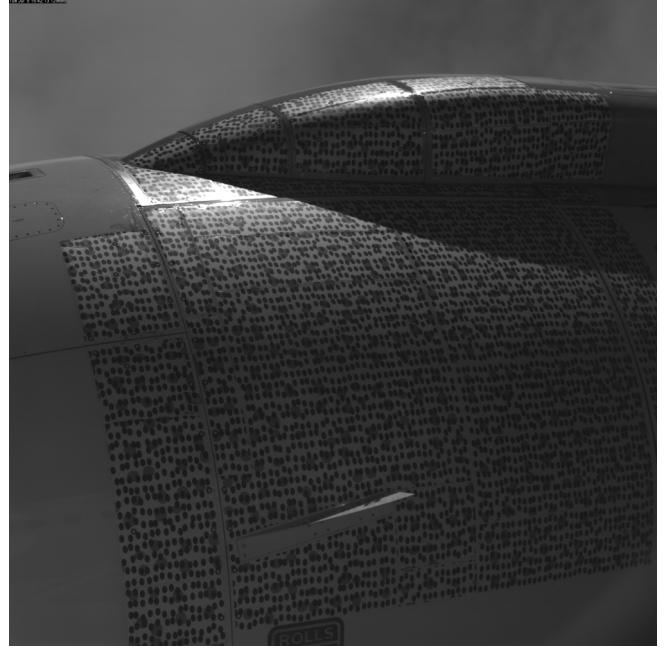


Figure 1: Global view of the monitored nacelle region. The figure illustrates the observed footprint, the multi-panel curved surface, and the presence of strong illumination gradients caused by operational outdoor conditions.

incidence angle. Some regions are observed nearly frontally, whereas others are seen under grazing incidence. Local occultations may occur because of protruding features or neighboring parts. As a result, the local signal content, the metrological sensitivity, and the practical exploitability are not uniform over the field of view.

3.2 Radiometric perturbations

A second difficulty is radiometric. In its simplest form, DIC assumes approximate grey-level conservation between a reference image $f(\mathbf{x})$ and a deformed image $g(\mathbf{x})$,

$$g(\mathbf{x}) \approx f(\mathbf{x} + \mathbf{u}(\mathbf{x})), \quad (1)$$

where $\mathbf{u}$ is the displacement field. In flight, this idealization is challenged by sunlight transients, cast shadows, non-uniform illumination, specular highlights, window-induced bias, and stray reflections. A more realistic formulation writes

$$g(\mathbf{x}) \approx \alpha(\mathbf{x}) f(\mathbf{x} + \mathbf{u}(\mathbf{x})) + \beta(\mathbf{x}) + \eta(\mathbf{x}), \quad (2)$$

where α and β account for local contrast and brightness changes, and η gathers residual perturbations. In practice, some of these effects only increase the residuals, whereas others locally destroy the information and must be treated through masking or confidence downgrading [14, 13, 15].

3.3 Calibration stability and long sequences

The stereo setup itself must also be considered as part of the problem. Cameras are installed in the cabin and observe the

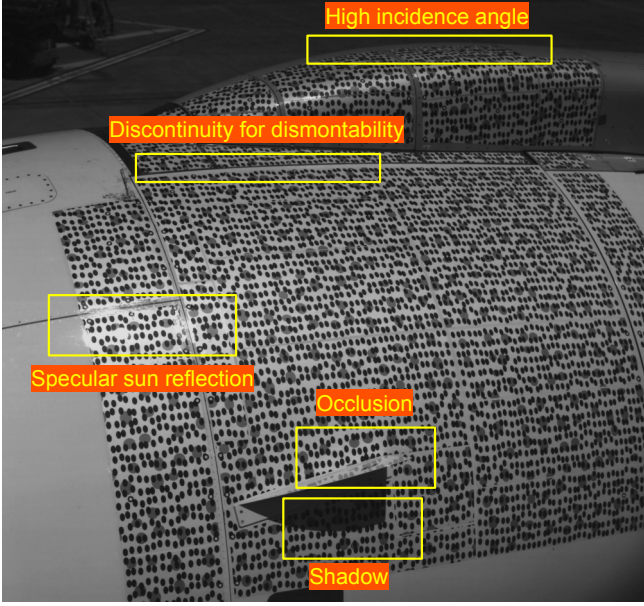


Figure 2: Representative practical constraints on the monitored nacelle. The annotated image highlights the main local difficulty classes encountered in the present configuration: grazing-view region, pattern interruption imposed by panel removability, specular reflection, local occlusion, and cast shadow.

nacelle through windows in a non-purely-metrological environment. Calibration therefore cannot be treated as permanently fixed without verification. In addition, representative campaigns generate long sequences and large image sets, so the processing chain must remain scalable and robust to non-exploitable frames.

4 End-to-end workflow

The workflow adopted here is built around five coupled blocks: surface patterning, camera-network calibration and operational revalidation, radiometric robustness, scalable global DIC processing, and confidence-oriented validation.

4.1 Pattern design under industrial constraints

Pattern design was driven by both metrological and operational requirements. Beyond the usual DIC criteria on grey-level contrast and feature size [8, 9, 10], the pattern had to remain compatible with large-area installation, multi-panel geometry, removability constraints, and observation under locally grazing angles. In the present case, a printed adhesive pattern was adopted, with sufficiently large features and a matte appearance to improve robustness against blur, underexposure, and specular sensitivity. The main local observation and patterning constraints encountered on the nacelle are summarized in Fig. 2.

4.2 Calibration and operational revalidation

The initial geometric model of the stereo system relies on standard calibration formalisms [11]. In practice, however, the calibrated configuration is not assumed to remain valid without control. Operational revalidation is part of the workflow. A useful indicator is the mean epipolar residual

$$e_{\text{epi}} = \frac{1}{N} \sum_{i=1}^N d(\mathbf{x}_i^{(2)}, \ell(\mathbf{x}_i^{(1)})), \quad (3)$$

where $\mathbf{x}_i^{(1)}$ and $\mathbf{x}_i^{(2)}$ are corresponding observations in both cameras, $\ell(\mathbf{x}_i^{(1)})$ is the associated epipolar line, and d is the point-to-line distance. Even when no online recalibration is performed, such indicators are essential to keep the measurement physically defensible. On complex industrial parts, CAD-based stereo calibration and shape reconstruction can also be relevant complements to traditional calibration workflows [12].

4.3 Radiometric robustness and global DIC

Radiometric robustness is handled through combined acquisition and processing measures rather than through a single correction step. Local masking or weighting is used for persistent non-informative zones, grey-level residuals are monitored to localize radiometric mismatch, and a global DIC formulation is used to exploit spatial coupling and regularization. In generic form, the minimized functional can be written as

$$\mathcal{J}(\mathbf{u}) = \int_{\Omega} w(\mathbf{x}) \left[g(\mathbf{x}) - \tilde{f}(\mathbf{x} + \mathbf{u}(\mathbf{x})) \right]^2 d\mathbf{x} + \lambda \mathcal{R}(\mathbf{u}), \quad (4)$$

where $\tilde{f}$ denotes a photometrically corrected reference image, $w(\mathbf{x})$ a local confidence or masking weight, and $\mathcal{R}(\mathbf{u})$ a regularization term. EikoTwinDIC was used in this global setting so that geometry-aware processing and confidence assessment could be handled coherently. Such integrated approaches can be naturally extended to account for grey-level and blur variations when optical conditions become strongly non-ideal [16].

4.4 Scalable processing and validation

The final stage of the workflow is validation. It combines residual-based confidence criteria, consistency checks on the measured field, cross-checks with independent sensors when available, and comparison with expected structural response. This philosophy is consistent with good-practice recommendations in DIC uncertainty assessment [20, 21, 22]. The complete logic of the proposed chain, from setup preparation to confidence-oriented validation, is summarized in Fig. 3.

5 Controlled perturbation study

A controlled stereo benchmark was used to assess how representative radiometric perturbations affect the correlation output and the associated confidence indicators. The investigated

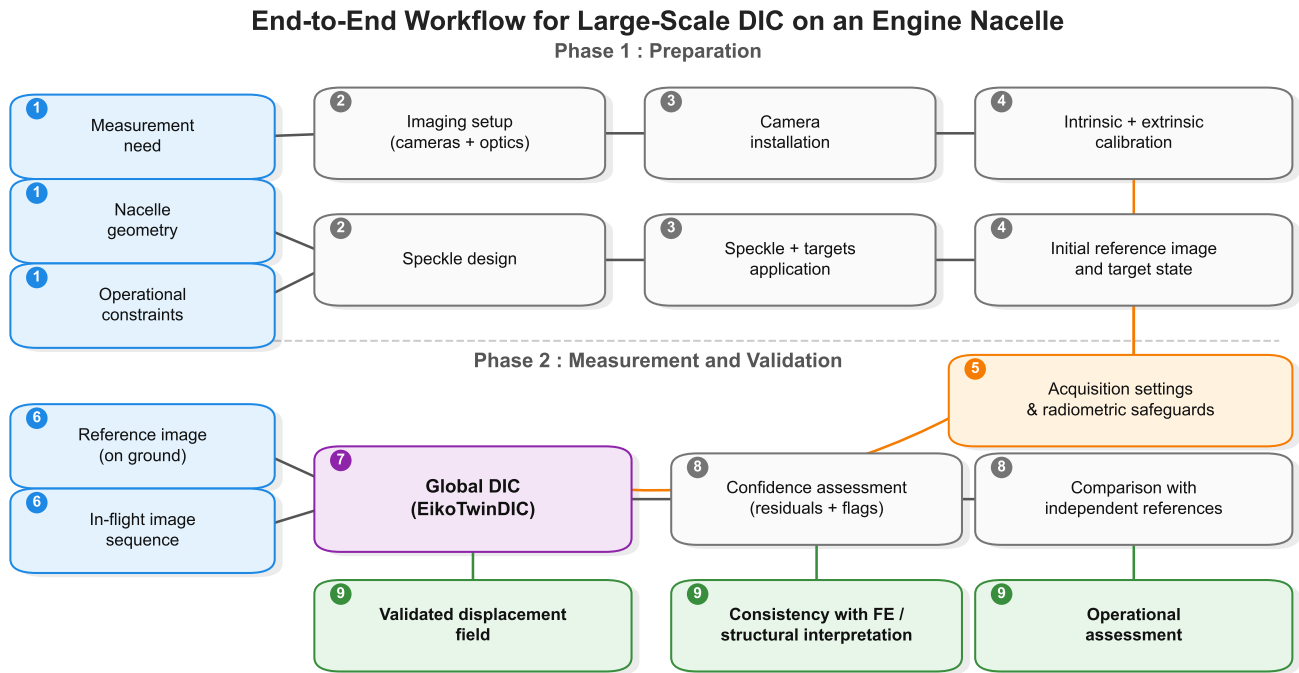


Figure 3: End-to-end workflow used in the present study, from measurement need and setup preparation to global DIC processing, confidence assessment, and final validation against independent references and structural expectations.

cases were organized into four distinct configurations: an unperturbed baseline (Fig. 4), a non-uniform illumination case (Fig. 5), a cast-shadow case (Fig. 6), and a window-induced stray-reflection case (Fig. 7). The purpose of this study is not to reproduce the full flight environment exhaustively, but to isolate several key perturbation mechanisms and to compare their effect on the residuals and on the local confidence maps.

The unperturbed baseline, shown in Fig. 4, is used as the nominal reference against which the other perturbation classes are interpreted. It provides the residual and confidence structure of the workflow when the radiometric conditions remain close to the underlying assumptions.

The non-uniform illumination case, shown in Fig. 5, addresses the effect of smooth grey-level variations that do not necessarily destroy the information content, but modify the local radiometric consistency. This case is representative of gradual illumination gradients encountered on large curved surfaces.

The cast-shadow case, shown in Fig. 6, is more severe because the radiometric change is spatially sharper. The corresponding residuals concentrate near the shadow discontinuities, and this is precisely where a confidence criterion becomes useful to distinguish locally degraded but still interpretable regions from clearly unreliable ones.

The last case, shown in Fig. 7, focuses on window-induced stray reflection. This perturbation is directly relevant to the actual flight-test configuration because the nacelle is observed through cabin windows. It introduces localized radiometric bias that is neither purely global nor strictly equivalent to a

cast shadow.

Taken together, Figs. 4, 5, 6, and 7 show that radiometric perturbations do not affect the measurement in the same manner. Smooth non-uniform illumination mainly perturbs radiometric consistency while leaving the measured geometry broadly stable. Cast shadows strongly increase the residuals at shadow interfaces, yet the confidence criterion can largely confine the affected zones. Window-related stray reflections generate localized residual growth whose effect is again moderated when the confidence metric is used consistently. By contrast, actual loss of information remains the limiting case and must be handled conservatively.

6 Representative flight-test results

The workflow was then applied to the nacelle under representative operating conditions. Four representative situations were considered to characterize the coordinate-noise levels:

- **G**: static aircraft with nearly constant sunlight,
- **T**: taxi with varying sunlight,
- **FC**: in flight with nearly constant sunlight,
- **FV**: in flight with varying sunlight.

The corresponding RMS coordinate-noise levels are reported in Table 1. They confirm that radiometric variability is one of the dominant contributors to uncertainty, but they also

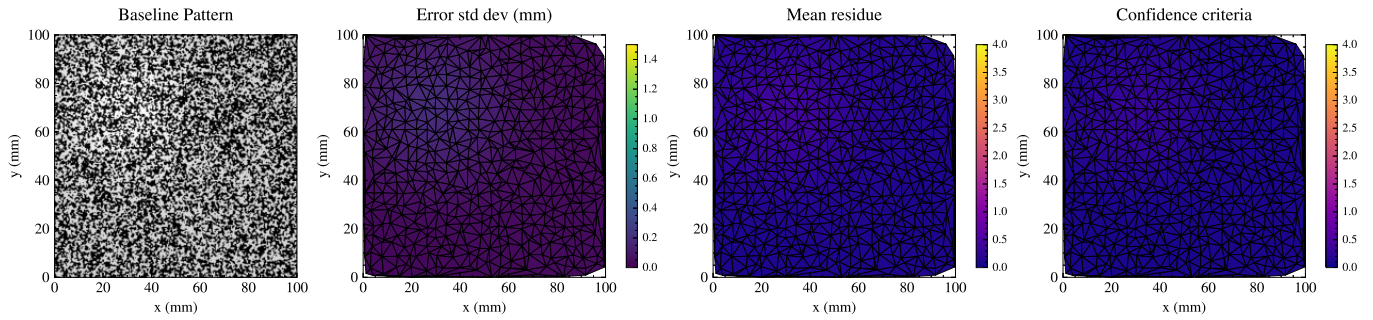


Figure 4: Controlled perturbation study — unperturbed baseline. This case provides the nominal reference for the interpretation of residuals and confidence maps under subsequent radiometric degradations.

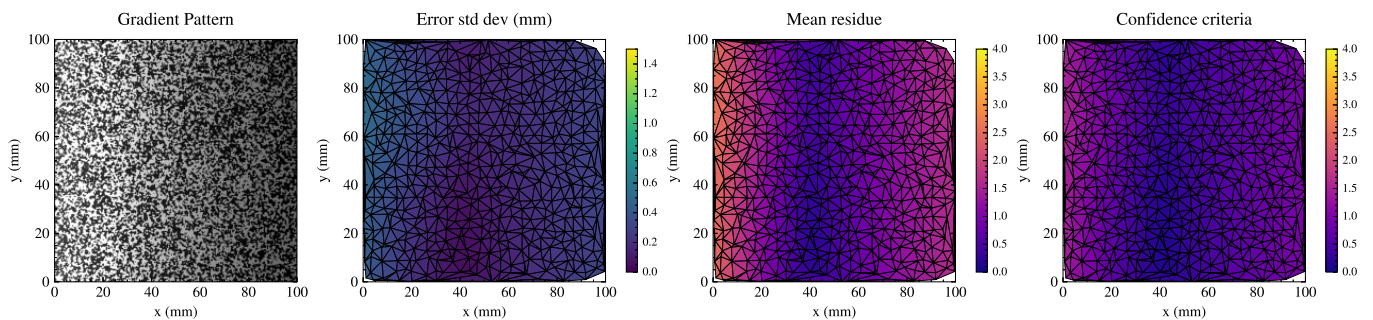


Figure 5: Controlled perturbation study — non-uniform illumination. Smooth illumination changes primarily affect residual structure while leaving the measured geometry broadly stable.

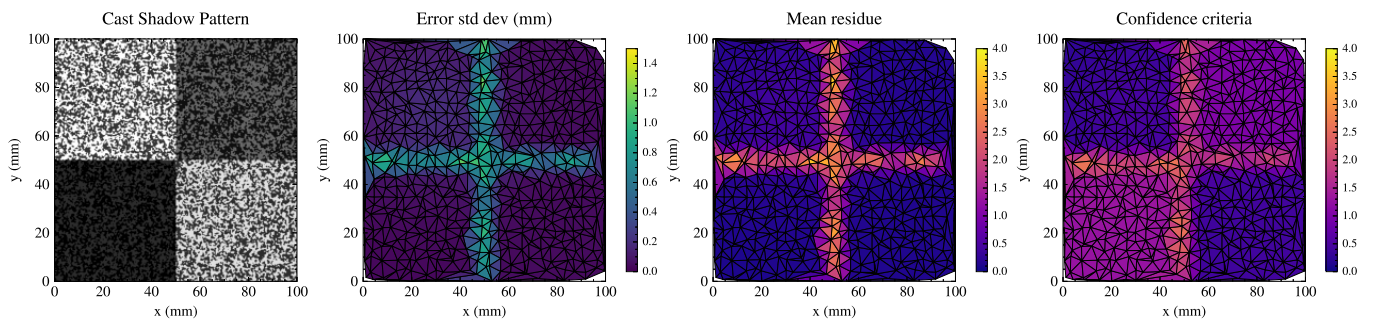


Figure 6: Controlled perturbation study — cast shadow. Shadow interfaces produce sharper radiometric discontinuities and stronger local residuals than smooth illumination gradients.

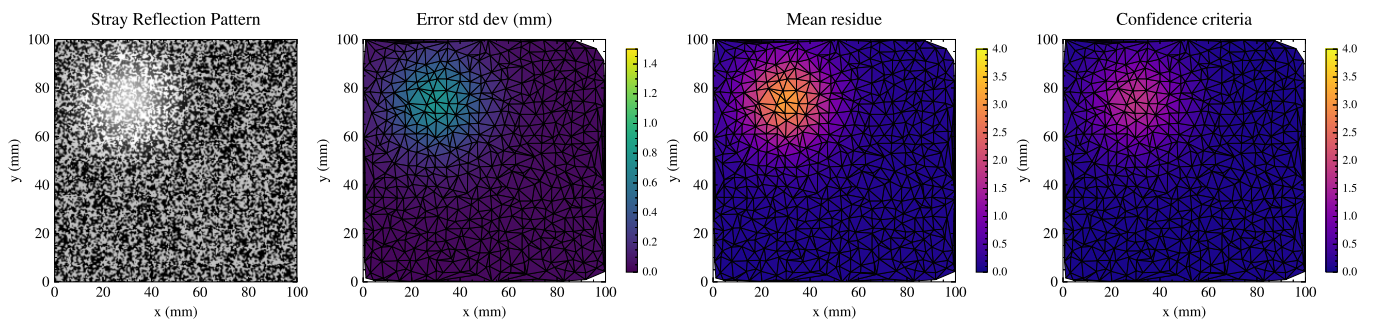


Figure 7: Controlled perturbation study — window-induced stray reflection. This case illustrates a localized perturbation directly related to the operational cabin-window observation chain.

Table 1: Representative RMS coordinate noise under ground, taxi, and flight conditions.

Condition	σ_X (mm)	σ_Y (mm)	σ_Z (mm)
G	0.02	0.04	0.02
T	0.10	0.11	0.11
FC	0.04	0.11	0.07
FV	0.06	0.14	0.08

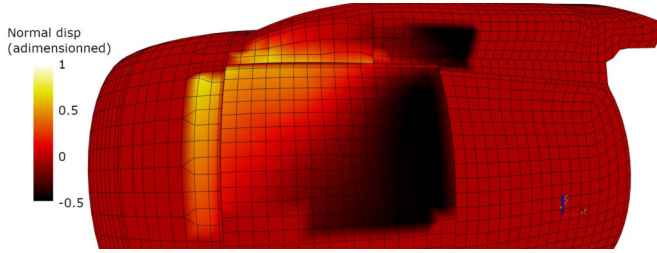


Figure 8: Numerical prediction over the observed nacelle footprint. This field provides the reference kinematic trend used for comparison with the optical measurement.

show that the displacement field remains exploitable in the targeted operating regime.

Whenever available, independent sensors provide an additional level of validation. In the present campaign, comparison with a displacement sensor measuring the relative motion between adjacent nacelle parts yielded a back-to-back RMS difference of 0.18 mm, consistent with the order of magnitude inferred from the full-field noise statistics.

The final comparison with the structural model is organized into three complementary views: the numerical prediction over the observed footprint (Fig. 8), the DIC-measured displacement field (Fig. 9), and the associated residual map (Fig. 10).

The first view, shown in Fig. 8, is the numerical prediction restricted to the observed footprint. It provides the expected kinematic trend against which the optical result can be interpreted.

The second view, shown in Fig. 9, is the DIC-measured displacement field itself. In the present conditions, this full-field displacement estimate is the primary physically defensible observable delivered by the workflow.

The third view, shown in Fig. 10, is the residual map. It localizes the regions where consistency is weaker and provides the spatial counterpart of the confidence-oriented interpretation advocated throughout this paper.

Taken together, Figs. 8, 9, and 10 show that the measured kinematic field remains consistent with the expected structural response over the observed footprint, while the residual map makes explicit where the comparison is weaker. This comparison is deliberately performed at displacement-field level, which is the most robust observable in the present operating conditions.

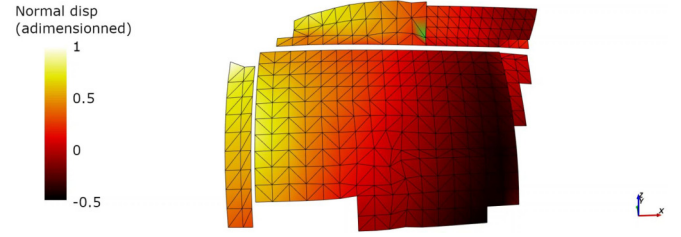


Figure 9: DIC-measured displacement field over the monitored region. The measurement captures the large-scale kinematic trend on the complex nacelle geometry.

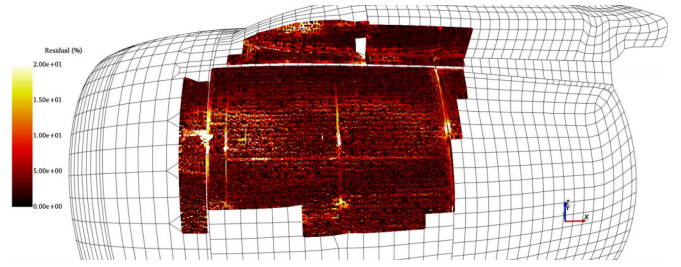


Figure 10: Residual map associated with the full-flight comparison. The residual field identifies the regions where agreement is weaker and where the interpretation must remain more cautious.

7 Discussion

The results support a simple conclusion: for large and complex aeronautical structures, robust DIC is fundamentally a workflow problem. Geometry, radiometry, calibration, processing, and validation cannot be optimized independently.

The first practical implication concerns the observable itself. In the present conditions, the displacement field is the most robust and defensible output. Strain, being derived from spatial differentiation, is substantially more sensitive to local defects, calibration bias, and regularization effects. This does not mean that strain is inaccessible in principle, but it should not be claimed indiscriminately on the basis of a visually plausible field alone.

The second implication concerns residuals and confidence. Radiometric perturbations do not all have the same consequence. Some primarily increase the residuals while leaving the measured geometry almost unchanged. Others create localized bias. Others remove the information. Residual maps and confidence criteria therefore play a central role: they indicate where the field remains trustworthy and where it must be interpreted cautiously.

The third implication is methodological. The interest of a global DIC framework in this context is not only numerical convenience. It provides a natural support for spatially coherent estimation, for geometry-aware processing, and for mesh-wise confidence indicators. Combined with operational calibration checks and careful pattern design, this makes it possible to deploy DIC on a genuinely complex industrial surface rather than on an idealized benchmark.

8 Conclusion

This paper presented an end-to-end workflow for large-scale DIC deployment on a complex engine nacelle in representative aeronautical operating conditions. The contribution lies at system level: pattern design, camera-network calibration and revalidation, radiometric robustness, global DIC processing, and confidence-oriented validation are treated as coupled parts of the same measurement problem.

The reported results show that useful full-field displacement measurements can be obtained on a complex nacelle under realistic constraints. Coordinate-noise levels remain sub-millimetric, and the comparison with an independent displacement sensor gives a 0.18 mm RMS difference. Controlled perturbation studies further clarify the distinct roles of non-uniform illumination, cast shadows, and window-induced reflections, and show the practical value of residual-based confidence criteria.

The main conclusion is therefore straightforward. On complex aeronautical structures, robust DIC is achieved when the full workflow is designed and interpreted coherently. In that setting, displacement is the primary robust observable, while future improvements are expected from tighter calibration monitoring, confidence-aware exploitation of long sequences, and sensor-fusion strategies coupling DIC with embedded instrumentation.

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