Health Monitoring of Structures in the Scope of Airframe Structural Testing

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Abstract. The development of large civil aircraft is an engineering task of significant complexity, requiring time and immense investment. The airframe development is subject to constant innovation in various fields of aerospace. The required testing of large-scale aircraft structures has shown to be time-consuming in itself. Structural Health Monitoring (SHM) can contribute to innovation in the way full-scale airframe structures are tested with the objective to reduce time and cost.
An overview on the motivation and associated requirements for use of SHM for airframe structural test is the basis to then define a conceptual framework and assess different SHM technologies with the intent of holistic and efficient application.
This work focuses on Guided Ultrasonic Waves (GUW) as the selected SHM technology for development, test and assessment, which was applied in a planned and structured way on a large-scale composite aerospace panel. The SHM system was adapted in terms of data acquisition as well as integrated with the overall test stand and a data management and data processing environment. That enabled the development of a dedicated signal processing framework for GUW data, in order to provide damage detection capability under the variable environmental and operational conditions of the test. The test set-up was representative for fuselage tests and solely available for the purpose of a research project. That allowed us to execute an experimental test program with specific conditions designed to assess the specific features of the SHM system and demonstrate the framework for data management and processing.

Keywords: Structures Test, Guided Ultrasonic Waves, Lamb Waves

Introduction

The development of large civil aircraft is a very complex engineering task, not only responding to the global market, customer needs and the drive for long-term economic success, but as well taking into account the societal responsibility for safe and ecologically sensible air travel. Airframe structural testing is part of the development validation and verification and commonly organized by a building block approach in the form of a test pyramid [1], enabling the certification of the aircraft. The necessity for full-scale fatigue testing evidence for new structure arises from Fatigue and Damage Tolerance certification requirements (cf. CS 25.571)
Such full-scale fatigue tests at the top of the pyramid are especially time-consuming and costly, but provide essential insight in the fatigue maturity of the product during the development considering fatigue phenomena only properly represented in a full-scale specimen.
Airframe development is subject to continuous innovation in various fields of aerospace, including structural testing. The reduction of full-scale fatigue test duration offers the attractive benefits to secure a high fatigue behaviour maturity earlier during the product development and motivated the research work to utilize Structural Health Monitoring (SHM) in fatigue tests presented here.

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1. NDI and SHM in the frame of structures test

Inspections take a particular role in fatigue testing. Their results are part of the test evidence as they shall determine if damage occurs and also characterize damage.
The concept of monitoring in conjunction with tests is of course not new. Section 2 will provide an overview on other test monitoring means commonly used, though usually not considered SHM.

1.1 Inspections in the scope of structural test

The primary objective of inspections is to provide test evidence on damage occurrence (or non-occurrence) as well as characterize the damage. A second objective is to ensure a safe and controlled completion of the fatigue test. Similar to inspections in the scope of production quality assurance and in-service maintenance, the utilized inspection method shall have a known performance and reliability. Especially for Non-Destructive Testing (NDT), communality with production and/or in-service NDT methods greatly facilitates the relation of test inspection outcome to the properties of the product, be it effects of potential acceptable manufacturing defect or to establish the detectability by a NDT procedure to be used in the maintenance program. Thus, a coherent basis for development, production and operation of the airframe structure is established.
The test inspection program is typically composed of different elements. Firstly, fatigue sensitive or otherwise damage prone structural items known by analysis are in the focus. The inspections shall detect, characterize the damage as well as capture the damage evolution over the test. Prior analysis guides inspection method selection, inspection threshold and interval, anticipating also maintenance needs. Secondly, unknown and unexpected damage phenomena (fatigue related or not) have to be observed. Here inspections shall primarily detect damage. This is actually a crucial but also challenging task. Thirdly, parts of the test specimen not under test (e.g. load introduction areas, secondary structure) shall be inspected to ensure safe completion of the test and correct loading.
Common limitations of inspections are general accessibility, hidden structures – and the fact that manual inspection cannot be performed while the test is in operation. The rigor and effort for inspections is subject to a trade-off. Direct cost and additional downtime are to be balanced against the reward of more and/or better information, while providing the minimum information connected with certification requirements.

1.1 NDT versus SHM

A fundamental difference between NDI based inspection and SHM is the ability of SHM to perform inspection with a much shorter interval, so the transition from a series of inspection tasks to an actual, quasi-continuous monitoring task. The effective detection capability of a continuous monitoring system would be a key characteristic of an SHM system, allowing substitution of NDT tasks by SHM monitoring tasks. Guidance on that subject can be found in ARP6821.
Most SHM methods do not readily allow judging about the severity of the damage, if they are designed for that purpose at all. In order to possibly establish a similar characterization of damages like standard NDT methods used for the product development, some development effort has to be anticipated, whose compatibility with a test project schedule should be an important consideration.
The development and adaptation need of an SHM technology dissimilar to the test of NDI methods used in the aircraft development in terms of development cost and time makes it not attractive to aim for a high-fidelity SHM technology just for test purpose. Wherever possible, SHM technologies and particular solutions also foreseen for the product should be used. In addition to that, there is an opening for low-fidelity, flexible technologies which can be used complementary to the existing NDI methods. In that case reliable damage detection and characterization is done by NDT inspection, while the overall inspection program is optimized with regard to test downtime, test risk and cost. SHM relies by definition on installed sensors, but their installation needs to be considered in the scope of testing in terms of feasibility, technical design, but also in time effort. Another particularity of most SHM methods is the need for reference, calibration or training data, which usually is at least partially unique to the structure under monitoring.

The requirements for SHM application vary significantly from an in-service application. Some general aspects relevant for test shall be mentioned here:

- detection capability according to the inspection task, or monitoring task, respectively.
- compatibility with test conditions, i.e. sustains test loading and environment, ruggedness
- compatibility with the specimen, i.e. no adverse effect on properties or structural behavior

Key enablers for SHM deployment are:

- robust operational integration in the test operation to ensure a real benefit, this might involve integration in the test data management and IT infrastructure
- physical integration of SHM system in the specimen and test rig, considering also other instrumentation, measurement systems and inspections
- commissioning of SHM system compatible with test sequence, reliability and maintainability ensured throughout the test operation
- SHM system design and implementation concurrently possible within the test schedule

1.2 Potential use and objectives of SHM for structural test

With respect to the aforementioned elements requiring inspections, SHM might be applied with the intention to cover known hot-spots, the surveillance of larger areas under test or non-representative parts of the test specimen not under test.
The inspection of known hot-spots makes up the bulk of the planned inspection over the test duration. The requirements are generally quite high. Occurring damages are usually to be inspected and characterized by the NDI methods used for the maintenance program. This leaves a relatively slim opportunity for SHM. If the SHM method is sufficiently sensitive, the planned manual inspections can be conducted on condition (condition-led inspection), thus increasing the efficiency of the inspection program while maintaining the power of standard NDT methods for damage characterization. A crucial point is the adjustment of sensitivity and avoidance of false-calls and related unnecessarily triggered manual inspections. A particular concern is to still enable conventional NDT in the monitored area.
The surveillance of larger areas for unexpected damages can be assumed to be done nowadays by periodically checking strain measurements and foremost visual inspections. The undefined nature of something unknown makes it quite difficult to detect, since the means put in place cannot account for its exact nature a priori. The significance of unexpected damage findings is related to the direct impact on the test and test schedule, as well as the potential impact on the product under development. Arguably, this is a good application field for SHM, as high sensitivity to gradual changes and high coverage of many SHM methods play to its advantage.
Fatigue initiation regularly occurs at hidden spots, such as mating surfaces in members of a joint, and visual inspection can be assumed to be less effective due to accessibility limitation. This can be addressed by SHM.
In order to save time and realize continuous monitoring, SHM should be performed continuously while the test is running to not depend on or create test downtime itself.

2. Test Monitoring Technologies and SHM

Health monitoring in the frame of structural tests can be differentiated in test rig monitoring and specimen health monitoring.
Test rig monitoring comprises all efforts to ensure that the test facility is functioning correctly over the duration of the test. This includes especially the control systems, measurement systems, load actuation and load introduction systems etc. This ensures that the test is conducted as specified with reliability and produces valid test results. Since fatigue testing involves transient load application, the control behavior opens an avenue to conduct test rig and specimen health monitoring at once. Degradation or damage impede the ability to apply the loads with needed accuracy or the deflections will exceed the expected envelope.

Health monitoring of the test specimen comprises any means put in place to directly or indirectly detect damages affecting structural integrity of the test specimen. There are on one hand common approaches like the comparison of static measurement results with model predictions on strain or deformation, or previous such measurements. An interesting approach was followed concurrently to the presented work, building on a digital twin of the test structure representing the structural behavior in a test rig [2]. Specimen health monitoring includes as well the NDI inspection program and commonly used crackwires. It can further include remote, non-contact NDI, like thermography and visual inspection by optical cameras, and can be based on measurement techniques like digital image correlation (DIC) [3] and thermal stress analysis (TSA). Another option is the application of established NDT methods like Phased Array Ultrasonic Testing with suitable sensors [4].
Several SHM technologies have been applied at various structural tests in the past already, a few examples: Fiber Bragg Gratings (FBGS) [5], Comparative Vacuum Monitoring (CVM) [6, 7 ,8], Acoustic Emission [8], Guided Waves [9].
However, the impetus of most applications was foremost the development of SHM technology for in-service use cases, seldomly the systematic improvement of structural testing.

3. GUW SHM for fatigue test monitoring

The technique utilizes a network of transducers to excite and sense guided ultrasonic waves propagating in the structure. Those waves have a sensitivity to damages which alter the wave propagation properties of the structure, but are also influenced by environmental and operational conditions (EOC), mainly temperature and stress state of the structure via the acousto-elastic effect.
This technology can be used very versatilely for different structural configurations and benign damage of different types, as long as suitable wave propagation through the monitoring area can be achieved. The long research history in the field yielded a multitude of different methods, algorithms, sensors etc.
While GUW can be thought of to be very sensitive, it is on the other hand difficult to calibrate the methods to achieve a good characterization of damages in practice. For the sake of application in test, the detection capability can already provide a significant benefit, as discussed in section 1. The main challenge to apply GUW SHM for fatigue tests during cycling is the effect of loading on the wave propagation and the sensors.
The SHM system used for this work is described in detail in [10] but is briefly introduced here:

- DuraAct sensors, packaged for easy application (see figure 2)
- Electronics for multiplexing to allow high number of sensors
- A *National Instruments* DAQ device with custom *Labview* software and a data management application
- Post-processing algorithms incorporating feature extraction and statistical models [11]

4. Demonstration

4.1 Test set-up and test plan

In the frame of a public funded research project, a composite fuselage panel was utilized for several development purposes, with GUW SHM being one of the technologies under study. This allowed us to specify the loading, fatigue spectrum and other test parameters for technology development. It also allowed use of dedicated test infrastructure featuring (see figure 1):

- Synchronization among the different measurement systems, incl. the SHM system
- A central Data Management System [12] connecting all data sources, such as strain gauges, control system outputs, DIC
- Execution of dedicated SHM algorithms in a post-processing framework (HBK *aquira*)

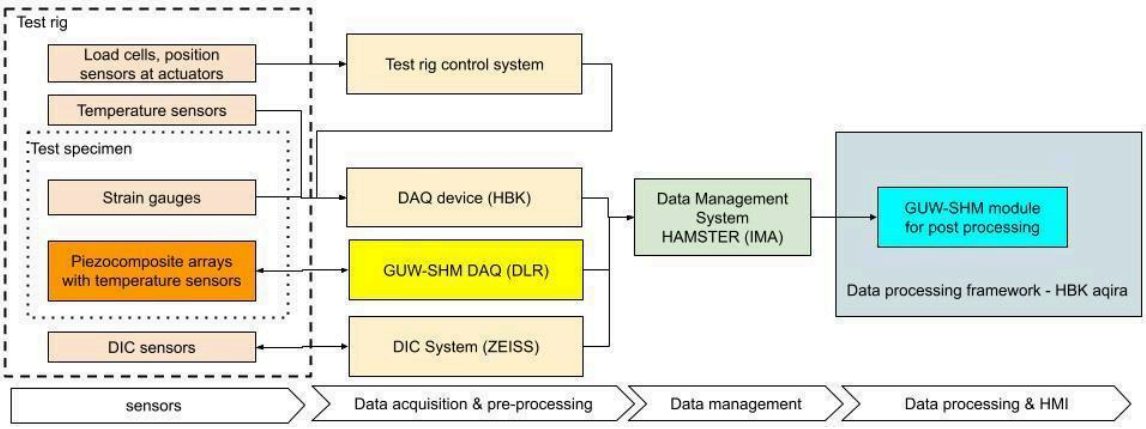

Fig. 1. : DAQ and DMS elements and architecture deployed for research purpose

The objectives of the demonstration testing were as follows.
Firstly, proper DAQ of the SHM system in the frame of dynamic fatigue testing was to be established. Prior work [10] was limited to static conditions.
Secondly, the integration of the SHM-system in the overall test infrastructure, such as synchronization and interfacing with the Data Management System was achieved.
Thirdly, the acquisition of a data set enabling the development of algorithms for EOC compensation during long-term tests. For this purpose data was acquired over a longer time period to have typical environmental effects, foremost temperature, and the dynamic loading represented in the data. Furthermore, reversible dummy damages and two additional impact damages were introduced.
Fourthly, the use of that data to progressively develop and test Gaussian Processes Regression (GPR) as an algorithm for damage detection under EOC [11].
The algorithm was finally run in the post-processing framework to demonstrate the complete chain.
The test structure, depicted in figure 2, was loaded typically for rear fuselage structures in a multi-axial test rig. Five basic load cases were defined (Vertical Bending Up/Down, Lateral Bending Left/Right) and axial Force), whose main directions of deformation are indicated in figure 2, from which a total of 27 different static load cases were derived. A simplified fatigue block load spectrum was synthesized, which each of the 12 blocks defined uses those 27 load cases as load points. The load level and frequency of occurrence of the blocks were chosen to form a log-linear distribution at 12 different load levels between 1.0 and 0.29. The order of the load points per block and the sequence of blocks were further randomized to form a sequence of 5773 simulated flights. This approach created a load spectrum of reasonable complexity for the purpose of SHM development testing.

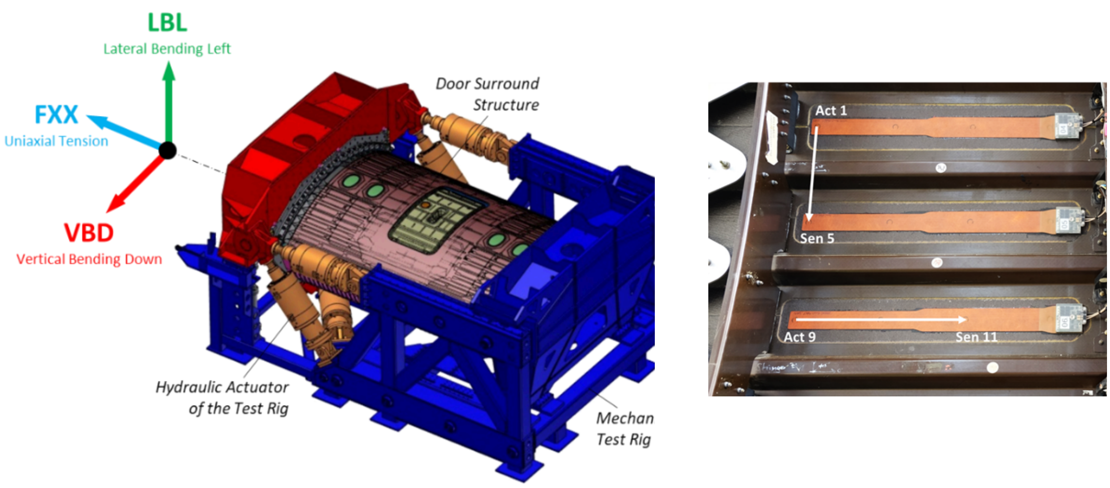

Fig. 2. Left: Sketch of test rig with test specimen and indicated loading directions [13], Right: Piezocomposite Arrays based on DuraAct^{TM} installed on the test specimen [10]

The test sequence consisted of the following main steps

- Test Commissioning phase, incl. SHM system test and integration test
- Static load cases, stepwise with 3 different load levels
- Harmonic pulsating loading of a single load cases as well as 2 combined load cases
- 1st fatigue phase (30.000 simulated flights), followed by static load cases
- Damage introduction followed by static load cases
- 2nd fatigue phase (ca. 45.000 simulated flights) followed by static load cases

The hangar conditions were uncontrolled in hot summer to cold winter season and the specimen was subjected to direct sunlight. This resulted in a wide range of ambient temperatures. The effect of changing insulation caused noteworthy temperature changes on a comparably short time scale.

4.2 Results

Gaussian Process Regression (GPR) is here applied to obtain a multidimensional statistical model, which is further utilized for damage detection accounting for the environmental and operational conditions (EOC) of the tested structure which otherwise would deteriorate the detection.
A selection of the applied loads (e.g. measured moments and forces) and measured temperature are selected as independent variables. The dependent variable is here the signal feature time shift (ToF difference) for a given actuator sensor pair.
The obtained GPR model is probabilistic by nature. It provides prediction intervals as well as the likelihood for a given new data point belonging to the data on which the model has been constructed by training data. For the purpose of the visualizations in this work a GPR model has been created by a set of measurements of one static load case at different load levels. Figure 3 (left) exemplifies the obtained model for one particular actuator-sensor connection and a set of data points related to a temperature range from about 13°C to 25°C and applied multiaxial loading at different load levels. It is visible that the prediction interval of the model gets noticeably larger outside of the temperature range as uncertainty increases. The figure 3 (right) provides a cross-section at 0% load level, with training data in black markers, data points at other temperatures are grey points. The colored points are additional test data points, whereas the color is scaled to the likelihood that the point fits to the model. The data point with the highest distance, and the lowest likelihood respectively, is in fact from one damaged condition, see also figure 5. This sensor path is just adjacent to an impact damage and has been selected for presentation as the benign damage effect on the signal feature is in the same order as the environmental and operational conditions.

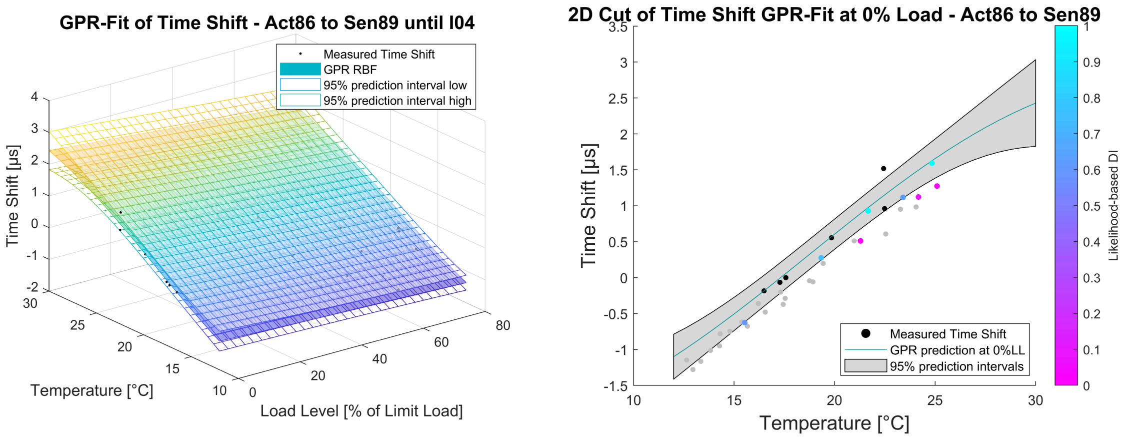

Fig. 3. Left: GPR model fitting time shift on temperature and load level; Right: GPR model with prediction intervals, showing training data as well as test data in undamaged and damaged condition

This shall highlight that a suitable damage indicator can be obtained from the GPR model output for each path and each measurement. The GPR approach has also the favourable property that the model trustworthiness, connected to the variance of the model at the conditions of interest can be used as well. Figure 4 shows the evolution of the measured time shift vs. the predicted time shift at

the related operational conditions for a larger number or measurements. The first sequence of 27 measurements is representing the training phase (black dots). The signal features are mostly well within the predicted range for most of the points. If the training data is locally too sparse, some training data points are not well predicted as visible here for one point.
The next 9 measurements are test data at undamaged structure with varying EOC, again colour coded by likelihood. The data points are within the prediction interval.
After that the structure was damaged by an impact. Accordingly, the last series of points are related to a damage condition at varying EOC. The measured signal feature change is in the order of the EOC but clearly out of the prediction range for the vast majority of remaining measurements. This highlights that the GPR approach enables the detection of benign damage under severe EOC.

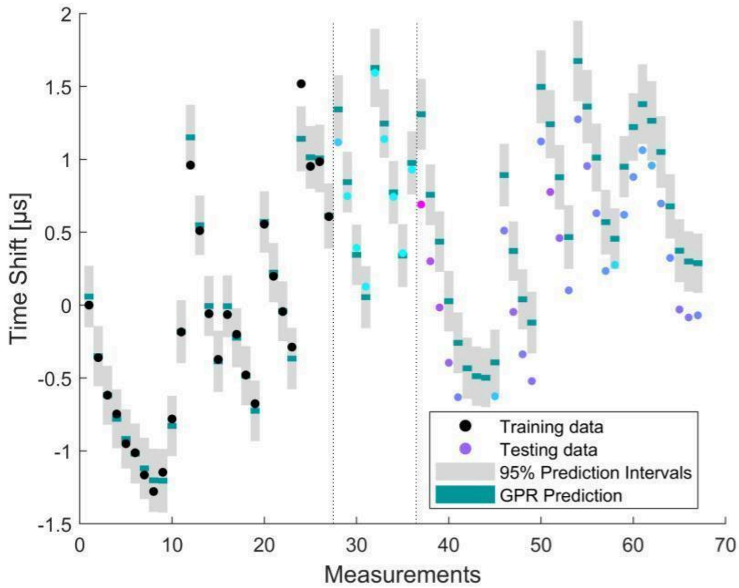

Fig. 4. Evolution of testing data prediction vs. measured signal feature for training data and test data in damage and undamaged condition

In order to demonstrate the damage detection by GPR with a simple algorithm, the likelihood-based damage indicator is used with RAPID (Reconstruction Algorithm for Probabilistic Inspection of Damage) [11]. Figure 5 shows the result for test data in a damage condition for two different load levels.

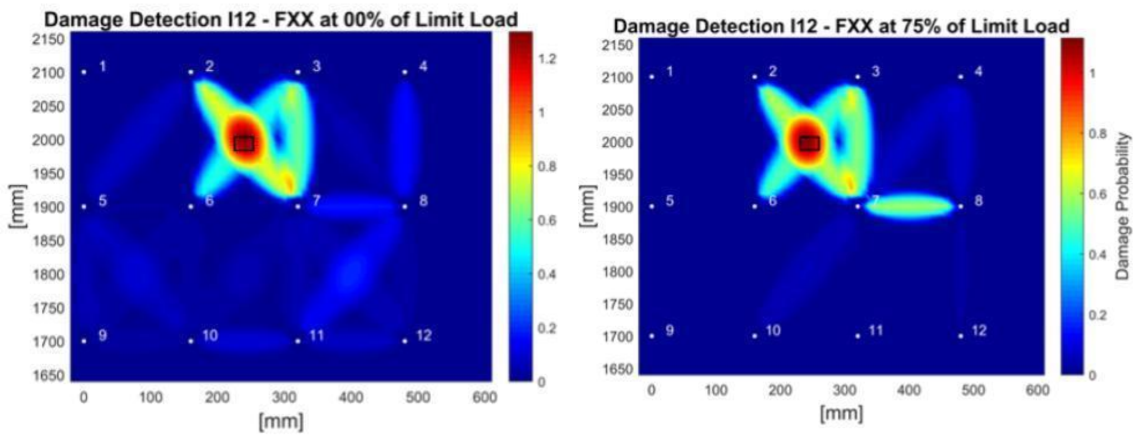

Fig. 5. Damage detection results at operational conditions (left: unloaded, right: 75% limit load)

The introduced impact damage is clearly identifiable, whereas there is no false detection for the undamaged condition.

5. Conclusion

The advantages of the GPR algorithm have been demonstrated: Inherent handling of the uncertainty related to sparse and noisy data, flexibility in handling non-linear relationships in the data and physical phenomena as well as scalability to large data-sets and multiple input and output variables.
The practical application within a fatigue test has been demonstrated, considering key enablers for test application in full-scale fatigue tests. This makes GUW-SHM a promising technology to raise the potential of SHM for full scale fatigue test applications.
The obtained data set will be used for research to account for other changes and degradation over the test duration, and related trend monitoring algorithms based on the developed GPR approach.

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