PERSPECTIVE

KNOWLEDGE BASED ENGINEERING (KBE) APPLICATIONS IN AIRCRAFT STRUCTURAL REPAIR

Abstract

Aircraft maintenance cost is the second highest cost incurred by aircraft industry and next only to fuel cost. Many flights are delayed due to maintenance issues and acute shortage of licensed mechanics. The need of the hour is to reduce this maintenance cost to make the aircraft industry profitable and sustainable. Owing to the fact that structural repair is predominantly knowledge and experience driven, Knowledge Based Engineering (KBE) applications assume criticality and hold promise to meet the identified challenges. This paper briefly presents landscape of KBE applications that can help in meeting some of the challenges in aircraft structural repair and maintenance.

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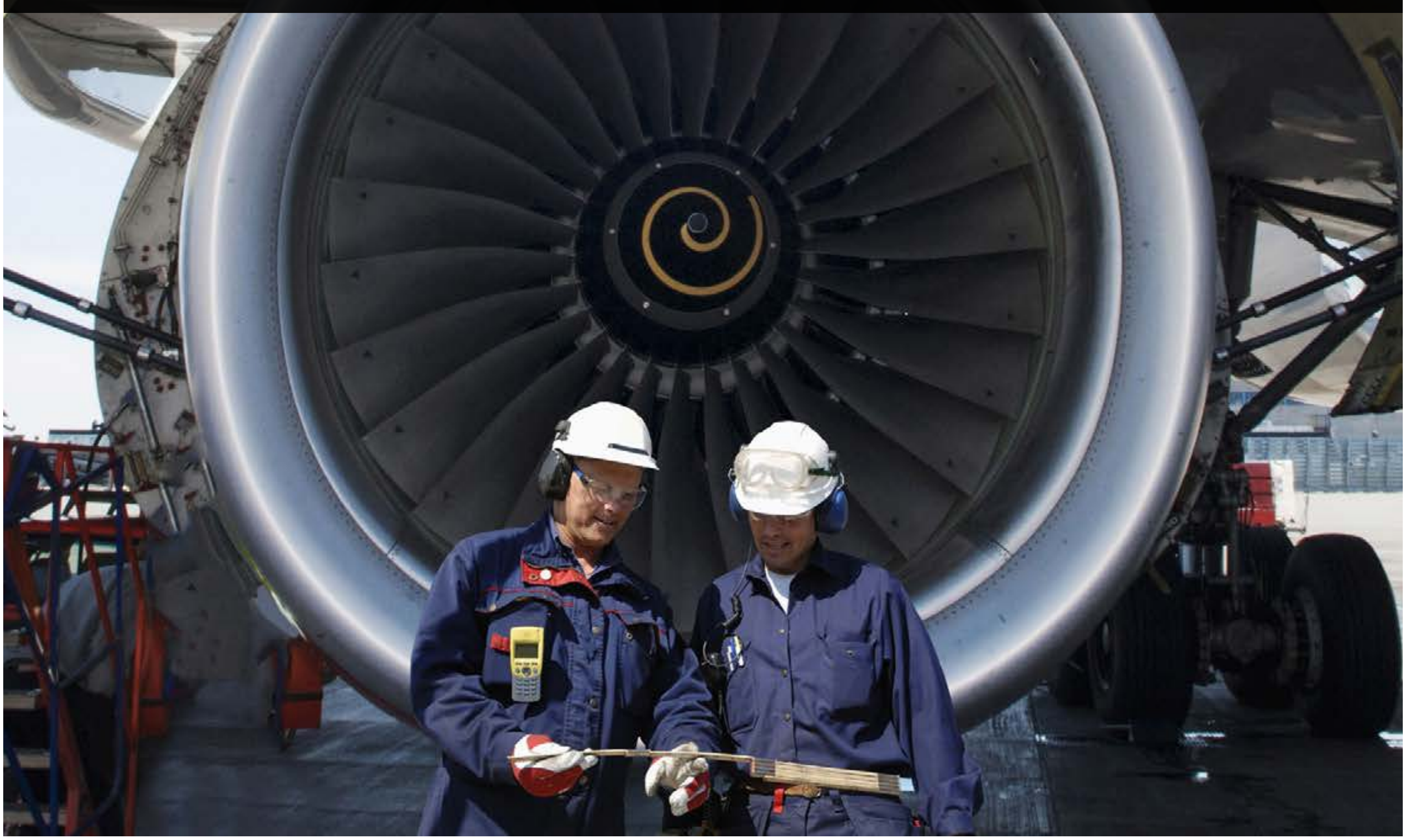
Introduction

The commercial aircraft maintenance, repair and overhaul (MRO) is a global business with multiple stake holders - Airliners, OEMs and MRO centers. About 20,000 commercial aircrafts comprising of more than 60 different aircraft models are in operation across the globe with more than 350 airline operators. Every aircraft in operation has to undergo scheduled and unscheduled maintenance, repair and overhaul at varied frequencies that are unique to an aircraft model. Owing to evolution and adaptation of new materials in airframe like advanced composites by various OEM's; the knowledge of repair procedures are mostly unique to specific aircraft models and is highly knowledge and experience driven. It takes huge amount of time and effort of the skilled technician. Moreover, aircrafts may have to undergo maintenance and repair at different MRO centers across the globe depending on their flight schedule. Similar type of maintenance and repairs may have to be carried out by different technicians at different geographic locations for various aircrafts. Hence, there exists tremendous opportunity to improve the productivity by capturing and re-using the knowledge of aircraft structural damages and repairs efficiently.

Knowledge Based Engineering (KBE) is an engineering product development technology wherein the knowledge of the engineering product and its design process is captured and embedded into a software system (known as KBE system) and utilizes such system in the design and development of similar new products. These KBE systems are then used by the designers to generate a new but similar product for a new set of input specifications. In fact, these KBE systems can be re-used to generate as many new but similar products. OEM's and Tier 1 suppliers use significantly KBE concepts in the design and development of aircraft structural components; incorporating the knowledge of multiple disciplines such as aerodynamics, stress, design, tooling etc. The same concept can be extended to structural repair as well, wherein the knowledge of the structural repair of an aircraft model can be captured and re-used in the form of suite of KBE applications for various phases of the repair cycle of the same aircraft model. The use of KBE concepts can be of significant benefit to OEMs, Airliners as well as MRO centres since all of them are involved in aircraft structural repair cycle.

This paper presents overview of MRO industry challenges, landscape of KBE applications that could improve the productivity and address the challenges of MRO industry.



Introduction

Overview of Aircraft MRO Industry

The commercial aircraft maintenance, repair and overhaul (MRO) is a global business with a market of $38 billion in 2007 and is expected to grow to $61 billion by 2017[1-3]. Aircraft airframe maintenance has a share of $8 billion in the overall MRO business and is believed to grow to $12.8 billion by 2017. MRO business is broadly classified into four categories– Line maintenance, Airframe maintenance, Engine overhaul and Component maintenance as described below:

Line Maintenance

Line maintenance is performed by Airlines which is highly labor intensive. It includes flight maintenance support, performing overnight services, A-Checks, B-Checks, trouble shooting delays and other maintenance services during aircraft operation. Daily, weekly and monthly checks are carried out and the aircraft goes back into scheduled service.

Airframe Maintenance

Airframe maintenance is also labor intensive activity and is predominantly controlled by airliners. It is normally carried out at the MRO centers. These include C, D and Intermediate checks. They cover majority of the scheduled inspections, hanger maintenance, engineering orders, deferred work items and additional work (due to the arrival of aircraft).

Engine Overhaul

This is controlled by OEMs of engines where in engines are inspected, repaired and overhauled. The activities include overhaul, disassembly, cleaning, inspection, disposition, internal / external repairs, testing and shipping.

Component Maintenance

Component maintenance is controlled by OEMs and covers dozens of activities dispersed over several ATA chapter listings. This covers repair and overhaul of components and major assemblies.

Typical business spend for each of these categories is shown in Table 1

Line Maintenance 23	Airframe Maintenance 21
Engine Overhaul 35	Component Maintenance 21

Category
% of spend

Table 1 MRO Business Categories and their Associated Spend Percentages

Major Challenges of the MRO Industry

Airframe maintenance is an involved process and significant portion of this pertains to structural maintenance. This is labor intensive as well as knowledge intensive requiring highly skilled technicians. On an average, an aircraft makes more than 40 maintenance visits (includes A, B, C and D checks) per year and with a maintenance effort of more than (12,000 hours per year). Many flight delays arise out of maintenance issues and acute shortage of licensed mechanics. The MRO industry faces many challenges due to presence of large number of aircraft types, globally spread airline operations and need for quick turnaround time.

The aircraft structural repair cycle involves many stakeholders like OEMs, Tier 1 suppliers, MRO centers and Airliners. Typically, to start with, the OEMs/Tier 1 suppliers identify most frequent damage scenarios and provide relevant repair solutions for all structural components. One of the major challenges is the efficient re-use of the previous aircraft program knowledge of various structural damages and repairs for the new aircraft programs. Though it is happening to a limited extent and in an unstructured manner, there exists enormous opportunity to effectively capture the previous knowledge to arrive at the damage and repair specifications for new aircraft models. But, this requires close coordination between Airliners, MRO centers and the OEM. In addition, OEMs are required to support Airliners on structural repairs of all the sold aircrafts. This requires increased involvement of structural experts of OEMs to support airliners and hence the number of experts required just to support the maintenance is huge. This results in shortage of experts for the newer aircraft programs.

Most of the scheduled aircraft maintenance checks are carried out at the MRO centers by the Airliners. The maintenance involves multiple aircraft models of multiple OEMs and requires diverse skill sets.

Conventionally, most of the structural repairs are carried out as per the instructions specified in the Structural Repair Manuals (SRM). These are voluminous documents and it takes large amount of time and effort to assess and identify the required repair procedures for a particular damage. More often, the MRO centers/Airlines will have to revert back to OEMs for the correct resolution. In addition, some of the damages and related repairs may not be in the scope of SRMs and thus it requires MRO centers / Airlines to revert back to OEM's. Obviously, this increases the turnaround time for carrying out the repair.

One of the major challenges that the airliners face is to reduce the ground time of the aircraft especially when the aircraft is in service schedule i.e. line maintenance. If there are any structural damages noticed during the line maintenance (Daily / A / B checks) of an aircraft, it is essential to get a resolution as early as possible. In many instances the flight gets delayed or even gets cancelled due to delay in the resolution to such damages resulting in increased maintenance and operational costs.

These challenges are summarized in Table 2 below:

OEMs/Tier 1	MROs	Airliners
• Knowledge capture and reuse from previous programs in development of repair specifications for new aircraft models. • Increased involvement of experts in repair services for in service aircraft models supporting the airliners, resulting in shortage experts for new aircraft program. • Increased need for aircraft reliability analytics	• Reduce turn-aroundtime (TAT) for repair services • High capability maturity expectation (quality) to address diverse repair incidents • Reduce operational cost • Shortage of skilled technicians	• High maintenance cost • High dependence on OEMs and MRO centers for repair services • Increased need for structural health monitoring and fleet reliability systems

Table 2 Major challenges of various stakeholders

It is essential to address these challenges in airframe maintenance through innovative solutions and Knowledge Based Engineering (KBE) concepts and applications can play vital role in meeting some of them.

Landscape of Aircraft Structural Repair

The aircraft structural repair life cycle begins at the design stage of aircraft development and continues till the aircraft retires from service. The stake holders in this cycle include the Airframe OEMs, Engine OEMs, Tier 1 suppliers, MRO centers and the Airliners. Figure 1 shows various phases of the structural repair cycle.

Original Component Design

The key stake holders of this phase are OEMs and Tier-1 suppliers. In this phase every structural component design is viewed from a damage/repair perspective for various kinds of damages and appropriate repair procedures are identified and approved by the relevant authorities and documented (i.e. Structural Repair Manual) as per the appropriate standard. This phase involves the following:

- Definition of allowable damage limit (ADL) criteria
- Load data storage and retrieval system
- Component 3D models, drawings storage & retrieval system
- Material data storage and retrieval system
- Allowable damage limits preparation
- Strength check notes preparation
- Structural Repair Manuals (SRMs) preparation

The output of this phase is a set of manuals generally known as "Structural Repair Manuals (SRM)". These SRM's are delivered to the airliners along with the aircraft by the OEM's. Thus the SRM's become an important and critical source of knowledge for the airliners for any kind of damage repair of aircraft.

Damage Identification

The key stake holders in this phase of the repair cycle are the Airliners and MRO centers. Every aircraft has to undergo an extensive inspection during its service. Many damages are detected during the inspection of the aircraft. The damage identification comprises the following activities.

- Regular Maintenance checks
- Ground handling damage incidents reporting
- Bird hit & debris hit damage reporting
- Lightening strike reporting
- Tool drop reporting
- Line station inspection reporting
- Others

The detected damage requires detailed assessment in order to decide on the repair resolution.

Damage Assessment and categorization

A damage detected may not necessarily require repair. Further investigation is required to understand the intensity of the damage, its location etc. This helps in arriving at the right kind of repair procedure.

This is normally carried out by the airliners or MRO centers who are involved in inspection checks. The damage assessment can be ascertained by use of one or more tests. Some of the damage identification tests include visual tests; tap tests, A-Scan, C-Scan, X-Rays, dye penetrants, thermal imaging, thermosonics, laser shearography etc. The type of test to be used will depend on the component type, damage location etc. Sometimes it may require multiple tests to exactly assess the damage. The outcome of this assessment will be the details of the damage such as its dimension, its exact location from the critical neighborhood features/ components etc.

Based on the details of the damage, the exact category of the damage (as specified in the SRM) will be identified. Some of the typical damage types include delaminations, disbands, core damage, edge damage, heat damage, impact damage, uneven bond line, weak bond and water in core etc.

While most of the typical damage types are covered within SRM, some of the damages (rare types which do not happen very frequently, such as bird strike etc) are not covered within SRM. For repairs of such damage types, the Airliners/MRO centers will have to revert back to the OEMs.

Figure 1 Various Phases of Aircraft Structural Repair Cycle

Repair Design

The repair design involves the following steps.

Identify the necessity of a repair:

Some of the minor damages may not require repair. The SRM provides guidelines on the allowable damage limits. In case damage does not require repair, then the rest of the phases will not be executed and the aircraft will be cleared for flight.

Classify the repair (SRM Repair or non SRM-repair):

While most of the damages are covered within SRM, there are some damages which are of special types and are not covered within SRM. Based on the SRM, it is required to identify whether repair procedure is given in the SRM for the identified type of damage.

Repair instructions:

SRM Repair: If the damage is already covered in SRM, then detailed repair instructions are taken from the appropriate SRM sections and used for the subsequent repair execution.

Non-SRM Repair: If the damage is not covered in SRM, then the damage is reported back to the OEM, who needs to come out with an appropriate set of repair instructions. This involves extensive work in terms of designing the repair and subsequent qualification. This is normally carried out by the OEM's

Generate repair design data:

This involves generating the required data for the execution of the repair. Airliners / MRO centers execute the repair within the SRM repair. However, non-SRM repair design is provided by OEM and the repair may be executed by OEMs or MROs.

Repair Qualification

This phase is applicable for non-SRM type of repairs carried out by OEMs. For the damages not covered as part of the SRM, the OEMs will define appropriate repair procedure which needs to be qualified as per the regulations and standards. The repair qualification typically comprises of the following activities:

- Idealize mathematical and numerical models
- Retrieve load data
- Perform FE Analysis
- Conduct analytical calculations
- Conduct strength checks
- Preparation of detailed repair qualification reports for certification

Once the repair procedure is qualified, the design data is released for executing the repair.

Repair Execution

This phase involves carrying out the actual repair by the Airliners/MRO centers based on the repair instructions and related data. The repair execution comprises of the following activities:

- Generate repair data for manufacturing
- Execute repair
- Document environment and process control parameters

There are many other aspects that need to be taken into account such as spare parts, logistics, tools/ fixtures etc. This phase also includes storage of repair execution data for future reference.

Repair Inspection and approval

The repair inspection involves verification of repair form, fitness and its confirmation in meeting the repair design specifications. The approval of repair completes the repair execution process.

Repair history capture

The repair history capture is essential to gather analytics for design enhancements and for conducting flight reliability assessment in addition to the maintenance of aircraft during its service life.

The data considered for archival includes damage information, repair design documents and other repair data. This involves diverse file formats like word documents, PDF documents, CAD models, images and other Meta data. This repair history database can be very useful information for both Airliner as well as OEMs for the future aircraft development as well as reducing the maintenance costs.

Knowledge Based Engineering (KBE) in Structural Repair

Knowledge based engineering (KBE) is an enabling environment to improve engineering product and its design process by knowledge capture and reuse. This is enabled through software and built upon well defined organizational processes and technology. Knowledge is defined as the skills, understanding and judgment of product and process built upon experience of an organization. This can be either tacit or explicit.

In the context of aircraft structural repair, KBE involves in capturing the aircraft model specific knowledge of various damages and related repair processes; and embedding this knowledge into suite of KBE applications for use across various phases of the repair cycle by various stake holders.

KBE frameworks and tools attempt to convert tacit knowledge available with technicians, and repair engineers to explicit form. As an illustration, the tacit knowledge of an expert being able to navigate voluminous SRM documents to make repair decisions through systematically querying the details on the damage incident can be transformed to explicit knowledge; so that experienced engineers and SMEs can focus more on innovative designs and newer aircraft developments instead of spending time on routine repair activities. Since the KBE systems can be used directly by the MRO centers or Airliners, there could be huge reduction in turn around time.

The essence of KBE technology is that it differentiates between an engineering knowledge from an engineering data; and enables capturing and embedding generic knowledge of the model specific repair aspects into KBE system. This enable re-use of the knowledge in an efficient manner for future aircrafts of similar model.

Another key consideration that could be of significant benefit is the use of structured KBE development methodology (such as Methodologies and tools Oriented to Knowledge based Applications (MOKA)) for repair related knowledge structuring and representation. The aircraft OEM majors typically adopt 5 year cycles to upgrade and transform IT technology platforms, and third party software applications that are needed for design and maintenance of aircraft. As the life of a commercial aircraft spans anywhere beyond 20 years, the migration of the design and maintenance related engineering data across changing platforms is inevitable. Hence it is a critical need to represent complex engineering data, design intent and other information related to aircraft components in formalized knowledge structures that are independent of IT platforms and third party commercial software tools.

KBE concepts, frameworks, methods and tools can help in meeting the major challenges faced by various stakeholders in aircraft maintenance. Prior to execution of repair many engineering activities need to be performed which can be automated and most of this repair design knowledge can be captured and shared to reduce the repair turnaround time and maintenance cost. This can be realized through effective deployment of KBE technologies. Thus KBE can help in:

- Enabling considerable productivity improvements, reducing maintenance turnaround time and maintenance cost
- Increased delegation of regular and routine sustenance functions to less experienced staff thereby relieving experienced staff for new product development activities and other innovation work.
- Reduced dependency on specialists, streamlined processes and enhanced quality control

Some of the potential applications of KBE concepts in various stages of repair cycle are summarized in Table 3. It also includes some of the software application areas which can bring in enormous productivity improvements to structural repair cycle.

Original Component Design	**PLM system interfacing utilities** • These utilities are needed to store and retrieve engineering data on repair design. The utilities are primarily clientside applications consuming web services hosted by CAD and PLM systems such as ENOVIA and CATIA V5. **Document management systems** • These systems play a crucial role in aircraft repair and maintenance. Voluminous documents with varying versions and revisions need to be maintained in respect of aircraft models as well as individual aircraft to meet the mandatory FAA requirements. Ex: SRMs, AMMs… **Legacy systems integration** • The technology transformation and migration in IT applications development happens approximately every five years at major OEMs, while aircrafts are designed for a life-span of 20 years. These systems help support usage of legacy tools such as Catia V4 and other OEMs In-house tools to maintain the old versions of aircraft. **Analytical tools** • Every design office has its own custom tools to conduct structural analysis and design fitness studies. As the number of such design aid tools runs into a few hundred for players in commercial aviation, their maintenance, upkeep and migration is a major activity. **Automated review work flow and collaboration systems** • Development of repair manuals and addressing an aircraft repair involves stake-holders from multiple disciplines/ work-groups (such as air-frames, structures, stress, loads, materials, repair, etc). The applications in this category facilitate exchange of engineering contents, online collaborative discussions, and work-flow management.
Damage Identification	**Incident tracking systems** • These systems help capture the first hand information from maintenance personnel and maintain databases of incidents reported. These will in turn be used during damage assessment and repair design **Fleet reliability systems** • The applications in this category involve development of data ware houses that in turn rely on databases populated by incident tracking systems. These will help study the reliability at various levels viz., aircraft model, individual aircraft, sub-assembly, component, etc. These systems provide vital clues in identification of design flaws, if any.

Damage Assessment and Categorization	**Repair diagnostics and categorization tool** • Repair diagnostics and categorization tools help interpret allowable damage limits data furnished through SRMs for various aircraft models. Such tools aid the repair inspector/technician to articulate and record/log the observed damage. **SRM assessment and interpretation system** • These systems help repair technicians navigate through wizard based user interface seeking context based inputs in order to arrive at the procedures to be followed to carry out repairs if need be as per the SRM recommendations.
Repair Design	**CAD data interchange tools** • OEMs partner with component vendors for design and development of aircrafts. As heterogeneous environment is inevitable and a reality today owing to diverse application platform priorities, scope for custom CAD data interchange tools exist. Generic tools and translators can only aid porting of standard features. However, aircraft design involves custom CAD formats which are a layer above the generic CAD data representation (Ex: MBD Vs CATPart). Such formats require custom treatment to import the CAD intelligence embedded into the seemingly generic CAD formats. **CAD utilities for repair design** • As with any domain, repair domain as well has certain repetitive design tasks which can be aided with automation tools, custom workbenches to speed up the design work. **SRM utilities** • SRM utilities help deal with intelligent retrieval of information from large voluminous manuals through advanced custom search utilities. **Repair history query utilities** • These are powerful custom search engines that work on various incident tracking system databases and repair databases to trace the repair history of an aircraft component or to understand the repair procedures followed in other instances of aircraft repair on other aircrafts bearing the specified similarities.
Repair Qualification	**Analysis tools for analytical approaches** • These tools deal with mathematical idealization of repairs such as single lap and double lap joints under tension and shear loading. They give good insight into the structural behavior derived from fundamentals **Analytical tools for initial design strength studies** • These are the tools developed based on the previous experience which lay-down the design rules for initiating the design trials before proceeding to formal design methods. **FE model generation utilities for solvers** • These utilities aid in transforming the detailed CAD Model into an idealized FE Model for studying the linear, nonlinear static behavior of the component. **Interface plug-ins to ESDU, MATLAB, SIMULINK, MATHEMATICA and MathCAD tools** • These plug-ins are needed to integrate with 3rd party commercial tools for structural analysis.

Repair Execution	**CAD utilities for repair manufacturing data generation** • The generation of manufacturing data in a prominent activity is executing any design, especially when dealing with composites their necessity is all the more important.
Repair History Capture	**Aircraft repair data warehouse** • The data warehouse is a must to enable conduct reliability analysis and also to facilitate aircraft and component second sale. **Fleet repair data repositories design and development** • These are a large voluminous work needed for maintaining the aircraft. **KBE based search filter constructs** • These consist of but not limited to filters that consider the topology, shape, loading pattern to retrieve structurally similar instances where repair has been addressed.

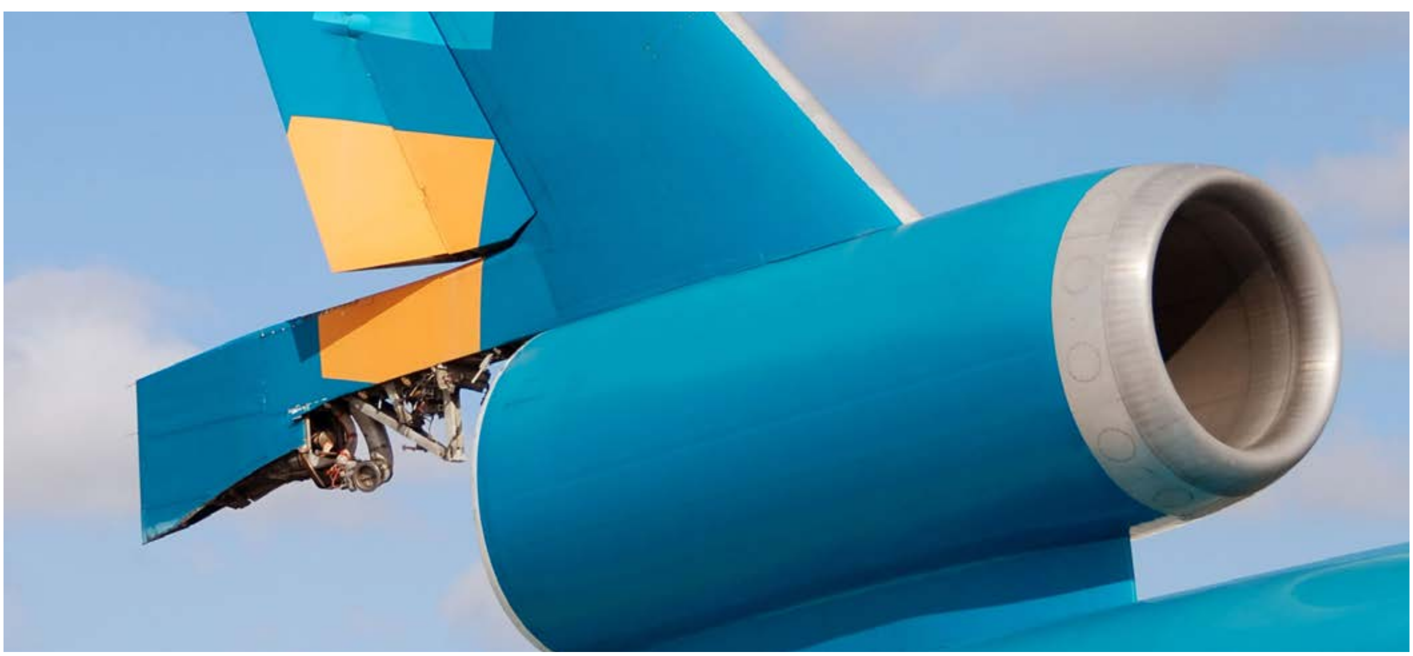
Table 3 KBE Applications in various Stages of Repair Cycle.

KBE is enabling technology which can bring in paradigm shift in the current aircraft maintenance and design process. The structured knowledge capture and reuse of damage and repair information through KBE can bring in substantial benefit of about 30% of overall maintenance cost for new technologies and materials like composites and hybrids.

Infosys is actively involved in developing various KBE frameworks, processes, methods and tools for aircraft structural repair in the past few years. Few proof of concepts (POC) tools have been developed to quantify the benefits realized through KBE in structural repair. One patent entitled "Framework for supporting repair processes of aircraft" has been granted from the US (US8670893B2) patent office on Mar 11, 2014. This patent describes how KBE can help in interpreting the SRM documents.

Thus the specific benefits of KBE in structural repair can be summarized as

- Significant repair cycle time reduction
- Reuse of repair knowledge from previous history
- Easier repair assessment and identification of repair procedures
- Reduced dependency on repair experts and skilled repair personnel
- Optimal and effective utilization of new inductions and less-experienced repair engineers
- Enables identification and bench marking of quality metrics for repair effectiveness
- Improved and consistent quality of repair execution
- Improved predictability and repair process execution reliability
- Enables fleet reliability and aircraft design reliability studies
- Facilitates lean systems implementation for exercising overall cost control



Conclusion

Aircraft maintenance cost is the second highest cost incurred by aircraft industry and next to only fuel cost. Each hour of flight requires about 10 person hours of ground maintenance effort. Many flights are delayed due to maintenance issues and acute shortage of licensed mechanics. The need of the hour is to reduce this maintenance cost to make the aircraft industry profitable and sustainable while reaching to common man. KBE is one such enabling technology to improve the productivity and reduce the turn-around time and thereby reduce the overall maintenance cost of aircraft. This paper presented how KBE can help in meeting major challenges of maintenance and repair in aircraft industry. KBE can bring in paradigm shift in the current aircraft maintenance and design process. The structured knowledge capture and reuse of damage and repair information through KBE can bring in substantial benefit of about 30% of overall maintenance cost.

Infosys is actively involved in developing various KBE frameworks, processes, methods and tools for aircraft structural repair in the past few years. Few proof of concepts (POC) tools have been developed to quantify the benefits realized through KBE in structural repair. One patent filed in US patent office recently in this area, is granted.

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