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Preface

This volume contains 45 technical papers from the 2019 Conference Fatigue Durability India. The theme of this 3rd International Conference was Fatigue, Durability and Fracture Mechanics. As in the past conference, the format consisted of keynote talks, invited lectures, contributed papers, exhibition and contributed posters. A total of 225 delegates participated in the conference, and 61 research papers were presented in Fatigue Durability India 2019.

Conference began with the domain experts Prof. Dattaguru, Former Professor, Indian Institute of Science, Bengaluru, India; Dr. Karisiddappa, Vice Chancellor, Visvesvaraya Technological University (VTU), Belagavi and Dr. Ravindra. R. Malagi, Technical Expert in area of fatigue, durability and fracture mechanics in nuclear energy, defence, aerospace and welded structures. This was followed by keynote talks from Prof. Dattaguru; Dr. Sam Kantimathi, President, Fatigue Concepts and Aging Aircraft Associates, California, USA; Prof. Vikram Jayaram, Professor and Chairman, Division of Mechanical Sciences, Department of Materials Engineering, Indian Institute of Science, Bengaluru, India and Shri. Prem Andrade, Senior Engineering Manager, ANSYS Inc, Pune, India.

Second day keynote presentations were made by Dr. A. Venugopal Rao, Head, Modelling and Simulation Group, Defence Metallurgical Research Laboratory, (DMRL), Hyderabad, India; Dr. Omar Ibrahim, MD Process Optimisation, USA; Shri. M. R. Saraf, Sr. Deputy Director, HOD—Technology Group, Structural Dynamics Laboratory, Environment Research Laboratory and Centre of Excellence for Fatigue and Materials, Automotive Research Association of India, (ARAI), Pune, India; Prof. Raghu Prakash, Professor, Department of Mechanical Engineering, Indian Institute of Technology, Madras, India and Dr. N. Narasaiah, Professor, Department of Metallurgical and Material Engineering, National Institute of Technology, Warangal, India.

The third day proceedings were further enriched by the following keynote speakers: Dr. Mikel Isasi Iriondo, Principal Researcher, Elastomer Material Durability, Leartiker Polymer Research Centre, Spain; Dr. R Sunder, Research Director, Bangalore Integrated System Solutions (P) Ltd. and President, Indian
The papers presented in the conference led to very good interactions addressing the structural integrity of critical engineering components in aerospace, nuclear, automobiles and railways, defence, power, petroleum and chemical industries.

In respect of aerospace, integrated life cycle management aspects covered structural joints, design and quality assurance requirements on the real-time warning sensors, gas turbine rotor blades, helicopter structures, launch vehicle systems subjected to vibration, system safety principles, cracked wing skin, heat exchangers in aeroengines, trainer aircraft airframes, superalloy IN718, landing gear systems’ functionally graded materials and surface modification of titanium alloys.

Low cycle fatigue and fatigue crack growth behaviour of critical components and weldments including the bimetallic pipe weld joints in the nuclear industry have been brought out along with life estimation strategy for nuclear reactor pressure vessel, corrosion fatigue in the compressor blade in a heavy duty gas turbine and fatigue crack growth in Ni-base superalloys. The remaining life estimation of thermal and hydro power plant components has also been discussed.

The structural integrity aspects of automotives and railways have been looked into from cumulative damage considerations as well as durability and reliability angle along with case studies.

The deliberations have also addressed the damage index of reinforced concrete structures, building structures, irregular reinforced-concrete-based isolated structures, FRP-confined columns, spring-integrated reinforced concrete hybrid beams, crack generation in rubber components used for tyre applications, non-linear behaviour in non-masking metals and impact of thermo environmental effects on optomechanical systems.

The conference ended with the awards of presentations to
(1) Mr. Shyam Kishore of GTRE, Bengaluru; (2) Mr. Puneeth Arora of BARC Mumbai; (3) Mr. Harish Babu of Wipro, Bengaluru, and Mr. Tarang Sinde, Visvakarma University.

The conference was sponsored by Ansys; BISS Bangalore; Software Technology Park (STPI); ICAT; Dassault System; SJC Institute of Technology, Chickaballapur; CadmarC Software Pvt Ltd.; Process Optimisation (Franc3D); Endurica; True Load and Publication Partner by Springer.

This volume contains 45 papers featuring significant aspects of fatigue durability and fracture mechanics emphasizing the multi-disciplinary subjects of fracture and failure, fatigue durability and life assessment dealing with different stages in the product life cycle management encompassing technological trends like digital twins, microscopic characterization, fretting fatigue, closing the gap between lab testing and engineering practice, high temperature corrosion, thermo-mechanical fatigue, fatigue of aerospace structural joints, combined LCF and HCF, residual stress and applied load on creep relaxation and failure of cementitious materials.
We thank all the sponsors, participants and exhibitors for their contributions to FatigueDurability 2019. We specially thank the authors and reviewers of the papers in this volume. Special thanks to all organizing committee members and programme committee members of FatigueDurability 2019.

Bangalore, India
Dr. S. Seetharamu

Bangalore, India
Dr. Thimmarayappa Jagadish

Belagavi, India
Dr. Ravindra R. Malagi
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About the Editors

S. Seetharamu received his Ph.D. in Mechanical Engineering from Indian Institute of Science in 1982 after obtaining M.E. in Mechanical Engineering from IISc in 1976 and B.E. in Mechanical Engineering from Bangalore University in 1974. Dr. S. Seetharamu worked in CPRI since 1985 till his retirement as Director in 2015. His areas of research interests are energy technology and materials engineering. Prior to joining CPRI, he had also worked in the industry and served as a faculty member at Toyohashi University of Technology, Japan.

Thimmarayappa Jagadish is the Technical Head of DHIO Research and Engineering Pvt Ltd., Bangalore. He completed his B.E, M.E and Ph.D in Mechanical Engineering from UVCE Bangalore University in the year 1983, 1986 and 1994 respectively, and worked as a Lecturer at RVCE, Bangalore from 1986 to 1996 and as an Assistant Professor at School of Post Graduate Studies, NITF, Bangalore. From 1999 to 2000 he worked as Head, Competence Design Center, Federal Technologies, Bangalore, and then at GE India Technology Center (now known as JFWTC, Bangalore) as CAE Specialist from 2000 to 2002. From 2002 to 2019 worked as Professor for Post Graduate studies, Professor and Head of the Department of Mechanical Engineering in Bangalore Institute of Technology, Bangalore.

Dr. Ravindra R. Malagi is a Professor in Visvesvaraya Technological University, India. He received his Ph.D. in Mechanical Engineering & Science from Visvesvaraya Technological University (VTU) in 2010 after obtaining M.E. in Design Engineering from Karnataka University Dharwad and B.E. in Mechanical Engineering from Karnataka University Dharwad and has previously worked as a Professor in the Department of Product Design & Manufacturing in Gogte Institute of Technology, Belagavi. His research interests include finite element method, design for manufacturing, rapid prototyping, tribology, advanced theory of vibration and the theory of elasticity. He has worked as a member of B.O.E, Mechanical Engineering at VTU and Deputy Chief Coordinator for VTU Digital Valuation.
Design Accomplishment for Unforeseen Discrepancies for Better Structural Strength and Fatigue Life of Helicopter Structures

Kalinga Gulbarga and A. T. Rao

Abstract Airborne structural parts are designed for critical operating flight and landing load conditions following the certification guidelines for enough strength and rigidity. But in the development test environments they will be subjected to loads differently than expected in the operating life unexpectedly leading to premature fatigue failures. Instances like fastener loosening due to loss of positive lock in primary attachments will trigger vibratory dynamic loads and fail the structural attachments. It is essential to avoid these unsafe situations by considering such events in the design. This paper aims at dealing one such instance practically observed during flight testing of helicopter. Redesign and analysis is carried out that show simulation of critical stress levels for dynamic vibration loads for fastener loosening effects and design accomplishment to avoid such premature structural failures and maintain original damage-tolerant behavior with better strength and fatigue life levels to meet operation life requirements.

Keywords Airborne · Positive lock · Vibration · Damage tolerance · Strength

1 Introduction

Helicopter structures are designed and flight certified as per approved international Federal Aviation Regulations [1]. The design criteria is that structural parts shall have the ability to withstand severe flight and ground operation loads without permanent deformation and last for its intended design life with no fatigue failure. During the initial design and development phase, the structural parts are analyzed for critical loading conditions for the static and fatigue strength using aerodynamically estimated loads. Also certification regulation calls for design of structural parts for ultimate loads arrived from operation loads multiplied with factor of safety. The objective is that structural parts shall not fail for specified design life and if failure happens, it
requires to survive until repair shows causing damage tolerance without diminishing strength for operation loads.

During development and flight testing phase, unforeseen instances may happen that have potential for structural damages and risk of catastrophic structural failures. The failure type, location, and size are neither genuine nor they are known from manufacturing process defects. It is important to monitor such instances, consider them in the initial design of primary structural parts of critical nature, and eliminate risk of catastrophic failures. One such practical event observed during helicopter flight testing is taken up for study as a case of design accomplishment. It is found in the inspection after helicopter flight testing that tail end horizontal control surface structural bracket near tail rotor got cracked and seen loosened bolt attachment. It could be due to loss of positive locking at the bolt nut and subsequent high “g” vibration loads at horizontal control surface could lead to structural bracket failure. Once again the structural bracket is redesigned with improved strength and attachment redundancy and verified its ability to sustain vibration fatigue loads apart from its regular operation flight load support capability.

## 2 Horizontal Control Surface Attachment

Horizontal control surface is an inverted aerofoil which contributes helicopter stability along the pitching axes. Its attachment is designed to withstand for maximum vertical load of push forward flight maneuver. The details of the horizontal control surface attachment are shown in Fig. 1.

The machined bracket is used to attach horizontal control surface laterally to the end of helicopter tail boom using quarter inch bolts. This horizontal control surface is assembled with vertical control surface for helicopter yawing stability. The total assembly will act as cantilever and transfers the span-wise and chord-wise aerodynamic pressure loads of horizontal and vertical surfaces to the helicopter tail boom structure through machined bracket. The vibratory load magnitudes if any due to stiffness loss will also transfer to the tail boom structure.

Originally, the machined bracket is stress analyzed for the critical push forward flight loads considering optimized attachments with quarter inch tension bolts. In the helicopter ground run flight testing, the bracket was subjected to vibratory dynamic loads \( F_x, F_y, F_z \) which are entirely different from design analysis load of push forward flight load case. The load path and magnitudes got changed due to disengagement of tension bolt and resulted in crack initiation on top flange corner stressed region of machined bracket. The cracked location and the loosened bolt are shown in Fig. 2.

The cracked bracket is replaced with newly redesigned bracket which is designed and analyzed to sustain vibratory fatigue loads from unexpected instances like nut disengagement in the operation.
3 Vibratory Fatigue Loads

As per regulations, it is mandatory to monitor helicopter vibration during flight testing to track whether the vibration “g” levels are minimum. The vibration “g” magnitudes in x-, y-, and z-directions captured in the flight testing of bolt loosing instance are shown in Fig. 3. The peak vibratory load magnitudes are observed at horizontal and vertical control surfaces in all x-, y-, and z-directions.
The estimated dynamic load magnitudes at horizontal control surface are \( F_x = 230 \text{ N} \), \( F_y = 140 \text{ N} \), and \( F_z = 340 \text{ N} \) and at vertical control surface are \( F_x = 260 \text{ N} \), \( F_y = 280 \text{ N} \), and \( F_z = 252 \text{ N} \). The bracket is redesigned considering these dynamic loads and verified for fatigue life.

### 4 Bracket Analysis Verification

During the design phase, horizontal control surface machined bracket is stress analyzed for critical push forward flight loads with tension bolt attachments. This machined structural bracket is later stress verified for vibration load magnitudes to understand the failure with boundary conditions of original bolt connections and loosened bolt condition separately. The dynamic vibratory loads \( F_x \), \( F_y \), and \( F_z \) of horizontal control surface and vertical control surface are applied and the stress variation across the bracket is obtained. These stress magnitudes are compared with the original flight push forward stress values and shown in Fig. 4.
The original design push forward flight case design stress level is kept at 60% of bracket allowable. The bracket is made of aluminum alloy material which has satisfactory service experience and good allowable strength. The bracket is safe for flight push forward load case as stress level is within the allowable limit. For the dynamic “g” loads, stress levels raised beyond design stress level and crossed allowable strength for the condition of loosened bolt. This maximum stress region is coincided with crack location. The stress magnitude for the loosened bolt condition exceeded the bracket material static ultimate strength and hence failure of the bracket occurred.

5 Bracket Redesign and Fatigue Strength

Most effective method is to design a lower stress level to improve fatigue life. The structural bracket is redesigned to improve the redundancy, strength, and fatigue life. Stress concentration at critical location is controlled by providing ribs and increase in flange thickness. For better fail safe design, redundancy in the bolt attachments is incorporated by increasing the number of bolts. The bracket is redesigned with these features and finite element model is created which is shown in Fig. 5. Analysis has been carried out for the improved design for the dynamic vibration loads. The magnitude of bracket stress obtained is shown in Fig. 6.

The redesigned bracket stress level is well within the allowable limit of material strength and met regulation safety margins of strength for the critical loads. This bracket has ability (toughness) to sustain stress concentration. The number of cycles of the vibration peak “g” loads observed in flight case is shown in Fig. 3. From the material SN curve [2], it is seen that the number cycles the bracket can tolerate for maximum stress is nearly $6 \times 10^7$ cycles (Fig. 7). The fatigue life estimated from these cycles using the time period is meeting component design life requirements. This design life estimated assuming flight test vibration loads is conservative and
Fig. 5 Redesigned bracket with bolt attachments and corresponding FE model

Fig. 6 Redesigned bracket stress plot for vibration dynamic loads

Fig. 7 Fatigue life cycles obtained from fatigue analysis [3]
such “g” loads will not be present in the original operating conditions. Even if such load comes the redesigned bracket is able to sustain these dynamic loads and fatigue failure is highly remote and safety is ensured. It is good to explore and visualize stress critical failure possibilities in the testing phase in the critical in unsafe condition primary structures and accomplish the design such that they will not lead to unsafe conditions.

6 Conclusions

Critical structural part design and analysis shall incorporate all critical failure possibilities that may likely to occur in development other than the usual operation design flight load cases. This will accomplish the design and maintain the desired level of damage tolerance, fatigue life, and reduce the fracture-related structural failures. It is very important that manufacturing and assembly process should not reduce the damage tolerance level required by the design.

References

1. Federal Aviation Regulations (FAR 27 amd 47–1)
3. MSC Nastran/Patran Fatigue manual
Design Optimization of Frame Rail Under Fatigue Condition Through FEA for Electric Drive Dump Truck

S. Suthakar and Y. M. Renukaraj

Abstract The objective of this study is to design optimized frame under fatigue condition through finite element analysis (FEA) for the off-highway electric drive dump truck. In today’s globalization world, the off-highway sectors started adopting advance technologies to get the optimized and reliable products. Nowadays, the off-highway vehicles have to be cost-effective and must have high power-to-weight ratio for the better fuel efficiency and to increase life of the critical components such as powertrain aggregate engine, alternator, etc. In the mining sector, desirability depends on the economics of operation in terms of ‘cost per ton’ of material transported. The cost per ton can be achieved only through the higher payload equipment and lower cost per ton approach. In case of open cast mine, the lower cost per ton can be achieved by adopting higher capacity dump truck with optimized weight and ease of maintenance of the electric drive dump truck. Therefore, this study has made an attempt to design the optimized frame rail size under fatigue condition through FEA method for the electric dumper. It covers how and when to adopt the optimization approach while designing frame structure. Also, it has emphasized that the fatigue load is one of worst load conditions for the frame design, where the complete frame will be twisted under left and right ramp conditions. Under these conditions, the optimum frame rail was designed with optimum plate thickness to meet the design criteria. The frame rail with different sizes and plate thickness were considered and analysed under the same alternate load conditions. Based on the historical data of frame with respect to the frame life, the optimized frame rail size and required plate thickness of frame were determined at the initial stage of design. This approach results in optimized frame and meets targeted power to weight ratio. Finally, this optimized design enhances the life of powertrain aggregates and improves fuel efficiency of vehicle.

Keywords Frame · Optimization · Dumper · Electric · Powertrain · FEA (finite element analysis)
1 Introduction

Energy needs of the country are continuously increasing and a major share is being met by coal-based thermal power plants. In order to increase thermal power generation to meet future demands, GOI has proposed to double the current production to reach 1 billion ton by 2020. India is richly endowed with abundance of coal deposits and this provides unique opportunity for generating electricity at competitive rates which is crucial for competitiveness of manufacturing sector and overall economy. In this backdrop, manufacturing high-capacity mining machinery in India is of crucial importance to ensure self-reliance and cost competitiveness of the energy sector.

Presently, open Cast mines are predominantly operated with mechanical drive dump trucks in the range of 35 t, 60 t and 100 t for removal of over burden as well as coal. Few larger mines of M/s Coal India are also operated on 170 t DC electric drive dump trucks which have been completely imported in the past. There is a plan by the coal mines to introduce 200 Ton class dump trucks in their mega projects to enhance rate of coal production. Currently, 200 Ton class dump trucks are principally available from overseas players like Caterpillar, Komatsu, Hitachi, Belaz, etc.

In this backdrop, BEML took the initiative to design and develop BH205E AC electric drive dump truck with several design features to enhance productivity, safety, operator comfort, and reliability.

In today’s competitive world, any product in the market is compelled to have reliable, optimal performance, low cost, better aesthetic and ease of maintenance. These factors have become key parameters of products in order to sustain in the competitive market.

In the mining sector, desirability depends on the economics of operation in terms of ‘cost per ton’ of material transported. The cost per ton can be achieved only through the higher payload and lower cost per ton approach. In the mining sector, especially for open cast mine, the lower cost per ton can be achieved by adopting higher capacity dump truck and easy maintenance electric-driven dump truck. Figure 1 shows the electrical-driven rear dump truck.

1.1 Problem Statement

In today’s globalization, challenges faced by dump truck manufactures are that of optimized design electric drive dump truck in order to meet the mining sector demand that is the economics of operation in terms of ‘cost per ton’ of material transported.

Therefore, this study has made an attempt to design the optimized electric drive dump truck frame structure through FEA. To achieve the optimum design, this study has adopted FEA approach at the conceptual design itself to determine the optimum frame rail size and plate thickness in order to have longer life at low cost. The other benefits of having the optimized frame structure at initial design stage are having low weight and to meet targeted power-to-weight ratio for the better fuel efficiency.
1.2 Comparison of Electric-Driven Dumper Over Mechanical-Driven Dumper

Figure 2 shows the comparison of electric-driven dumper over mechanical. A few advantages of electric-driven dump truck over mechanical-driven dump truck are lower lifestyle costs such as less gear, bearing and no brake wear, easy maintenance and low cost, higher power, speed and space resulting to the economic operation.

2 Frame Design Methodology

The space claim model is initial stage of frame design and created by accommodating all the critical aggregates. It is conceptual design stage for creating space for the major aggregates such as powertrain, electrical system, hydraulic system, brake system, exhaust system fuel system, etc. In the space claim model of frame, mounting location of these aggregates was fixed. These mounting locations and its load were inputs for the designing of optimized frame under the cyclic load condition to have better fatigue life.

A few novelties of this study are, it has adopted the design optimization of frame rail size at the initial conceptual design stage itself and the required plate thickness to
Fig. 2 Electric-driven dumper versus mechanical-driven dumper

withstand the load and meet the design criteria through the FEA and it was evaluated by theoretical method also.

2.1 Frame Analysis Model

The conceptual frame design model was created by using CAD software. At the initial stage of design, the major aggregate mounting locations were fixed tentatively and with these data the centre of gravity of frame was calculated. Figure 3 shows 3D model of optimized frame design.
2.2 Design Criteria of Frame

Based on the historical data of dump truck and field data, the frame should be designed for 40,000 h (that is, having approx. fatigue life of ~60,000 number of cycles) and the stress value at the critical joints of frame should be within 483 MPa.

3 Results and Discussion

3.1 Frame Rail Sizing

The determination of optimal rail size is the most crucial stage in frame design for finding out the appropriate plate thickness of rail. Figure 4 shows the frame rail sizing under 2G condition, that is, left and right ramps through finite element analysis.

The frame structure is considered to be the load bearing structure to support and withstand the major loads such as payload, body structure weight, powertrain system and other system. It acts as back bone of vehicle and to withstand various loads such as bending, torsion, braking, etc. Among these load cases, the torsion load (also known as twisting load) is considered to be worst load for the frame structure to be fatigue condition. Under this torsional load, the complete frame structure will be
twisted about its structural axis to the left and right ramp conditions (to be fatigue condition).

The optimum frame rail size and plate thickness were determined under this fatigue condition (that is, twist load). The stress value of frame rail is within the material yield strength and design criteria.

The frame rails with different sizes were modelled and analysed under the same load condition. Frame rail strength analysis was carried out under the maximum torsion load with 2G condition. These load conditions have predicated effectively the frame width and depth to withstand the maximum load under 2G conditions.

The analysis, nearly 14–16 iterations, was carried in order to find out the optimum frame rail size and required plate thickness for frame.

The plate thicknesses for bottom, side and top side of frame were determined based on the FEA analysis. The frame models of width at 200, 225, 250, 275 and 300 mm were modelled and analysed under the same load condition in order to determine the optimum frame width and depth and plate thickness to meet targeted design criteria and within the material yield strength. Figure 5 shows the FEA analysis result of two frame rail size.

From a fatigue standpoint, it is assumed that the frame must endure cyclic loading that oscillates between that left ramp and right load cases. Therefore, subtracting the results of the right ramp load case from the left ramp load case yields the full range of cyclic stress. Figure 6 shows the frame rail size FEA analysis result.

From the FEA analysis of frame, it indicates clearly that the frame rail size in range of 200 to 280 mm shows the stress value within the design criteria and material yield strength. The required plate thickness of frame rail and optimum size were determined through the FEA approach. The optimized frame design meets the international dump truck manufacture design standard (competitor models specification) and meeting the rail width and plate thickness and other design requirements such as power-to-weight ratio value and wheel base and wheel track.
**Fig. 5** FEA analysis result for the different frame rail sizes

**Fig. 6** Frame rail size FEA analysis result
4 Conclusion

From this study, the optimized frame rail size and required plate thickness were determined and the frame rail was designed under the torsional load condition (fatigue left and right ramp conditions). The space claim model is initial design stage and is created by accommodating all the major aggregates. The individual component location and load were considered as design inputs for frame design. Under the torsional load, the complete frame is subjected to the twist condition to left and right ramps. Based on the historical data on dump truck, newly designed optimized frame structure meets the number of cycle 60,000 cycle condition and stress value with the design criteria and material yields strength.
Total Technical Life Extension Techniques for a Trainer Aircraft Airframe

K. Manonmani, U. A. Acharya, and Appasaheb Malagaudanavar

Abstract Today, many ageing aircrafts in air forces of many countries are in service beyond their designed total technical and calendar service life. In general, typical military fighter and trainer aircraft airframe structure is designed for a service life of 20–30 years. The life extension programmes are being undertaken today for ageing aircraft considering the non-utilization of aircraft to its full potential, high acquisition cost of an aircraft limited by defence budget. This paper presents on the total technical life extension of an IAF (operator) trainer aircraft with initial Total Technical Life (TTL) of 8000 h. TTL extension programme has been carried out with operator formed task team including HAL and certifying agencies to extend the TTL of airframe beyond 8000 flight hours. Life extension studies consisted of full airframe (viz. fuselage, wing, tail plane and engine mounts, etc.) with respect to strength and fatigue life analysis margins, full scale fatigue test results, post-test inspection reports, histories of earlier overhaul data, material ageing aspects (considering environmental degradation, corrosion prevention and protective coating, wear and tear), ‘g’ exceedance and hard landing data, incident histories and repair scheme implemented on service aircraft. Additionally, TTL attained two lead aircrafts were strip opened, thorough inspections suggested and results were studied. After these extensive studies, the task force concluded that TTL of trainer airframe can be increased by 500 flight hours. Hence, as per recommendation, TTL of the aircraft extended to 8500 flight hours. Considering the present usage rate in fleet, the extension will ensure availability of trainer aircraft for training in another 4 years, thereby benefitting the operator for performing the intended tasks.

Keywords Total technical life (TTL) · Trainer aircraft · Full scale fatigue test (FSFT) · Fatigue modifications (MODs) · Material ageing · Inspection · Crack detection (CD) · Incident histories · Pre-survey

K. Manonmani · U. A. Acharya · A. Malagaudanavar
Aircraft Research and Design Centre (ARDC), HAL, Bangalore, India
e-mail: aa.udupi@hal-india.co.in

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1 Introduction

Total Technical Life (TTL) extension programmes are being undertaken nowadays to meet the current and future mission/training requirement using existing fleet. The programme aims at ensuring the airworthiness requirements of the ageing aircraft for performance beyond initial assigned life and the assets are used to its full potential life. Extending the TTL requires various approaches for analysing all the occurrences on the airframe fleet and evaluation of study results. This will facilitate prediction of the remaining service life beyond originally awarded.

The present paper discusses on typical trainer aircraft, which forms the backbone of Indian Air force (operator) ab initio pilot training program. The trainer fleet has served operator for more than five decades and majority of them are approaching end of its awarded service life. The trainer aircraft was designed, developed and manufactured by HAL. Initially, design service life of the airframe was assigned as 5000 flight hours. The designed service life is the period of time (viz. flight cycles, flight hours or landings) established at design, during which the structure is expected to maintain its integrity when flown to the expected loads and environmental spectrum. The subsequent Full Scale Fatigue Test (FSFT) of this trainer airframe specimen had revealed that there is a potential for extending technical life of the airframe beyond this. In this case, fatigue cracks observed at various stages during testing were repaired and the test was continued till the major load-carrying member failed, wherein the test was stopped. Later Fatigue Modifications (MODs) were regularized in fleet as compliance at specified flight hours to achieve the target fatigue life of airframe. As on today, TTL of airframe was extended from originally assigned design life of 5000 flight hours to 8000 with applicable MODs at different stages.

Owing to the operational requirements, operator is requested to study feasibility of TTL extension of trainers for exploitation beyond 8000 flight hours.

Note Due to confidentiality, aircraft name is not mentioned.

2 TTL Extension Study Initial Requirement

The program requires a team of all stakeholders, viz customer, manufacturer and certifying agencies (CEMILAC & DGAQA) for studying at various aspects involved in TTL extension which ensures airworthiness and structural integrity. Two lead aircraft (i.e. operational trainer aircraft having life nearing 8000 flight hours) are required for strip examination and detailed study by the joint team. Two lead aircrafts with 7991.20 and 7999.15 h were made available for the studies. An acceptable route to airworthiness post study agreed by the stakeholders.