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Fatigue Crack Growth Arrestor for High Speed Flexible Coupling of Fighter Aircraft Transmission Systems

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ABSTRACT:

A lightweight High Speed Flexible Coupling (HSFC) is used to connect the engine gear box (EGB) with an accessory gear box (AGB) for fighter aircrafts. The HSFC transmits the power at high speeds ranging from 10000 to 18000 rpm from the EGB to AGB. The HSFC also accommodates larger angular and axial misalignments resulting from differential thermal expansion of the aircraft engine and mounting arrangement. The HSFC utilizes series of metallic contoured annular thin flexible plates. These flexible plates are susceptible to fatigue failures in the presence of minuscule surface defects. The present work describes the analysis carried out on a typical HSFC with incipient flaw for various kinds of imposed misalignments. Based on the sensitivity study of the flaw on the stress levels, a Fatigue Crack Growth Arrestor (FCGA) is designed. In order to contain the crack propagation, drilling a hole at the tip of the crack on the flexible plate as a FCGA is adapted. The fatigue life of the flexible plates is improved by finding appropriate size and location of FCGA through finite element analysis and simulations.

KEYWORDS:

Flexible plates; Fatigue life; Finite element analysis; Fatigue analysis; Transmission systems

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1. Introduction

The fighter aircraft transmission system consists of a light weight High Speed Flexible Coupling (HSFC) known as Power Take-Off (PTO) shaft for connecting the engine gearbox (EGB) with an accessory gear box (AGB). The HSFC transmits the power through a series of specially contoured metallic annular thin flexible plates whose planes are normal to the torque axis. The HSFC operates at high speed ranging from 10000 to 18000 rpm from the EGB to AGB. These flexible plates are made up of titanium alloy. These are designed to cope with the operating conditions, misalignment requirements, dimensional restrictions and safety [1]. The HSFC also catered for accommodating larger angular and axial misalignments resulting from differential thermal expansion of the aircraft engine and mounting arrangements. The misalignment is the deviation of relative shaft position from a collinear axis of rotation, measured at the point of rotation [2]. The misalignment may result in excessive vibrations [3].

Thinner cross sections of flexible plate help to accommodate the axial and parallel misalignments by elastic material flexure by maintaining low bending and axial stresses for a given torque capacity. The parallel misalignment and axial displacement distorts the flexible plates. Most failures in HSFC occur due to high cyclic stresses imposed by misalignment and fatigue. The fatigue strength of the flexible plates depends on the surface finish of the contour. Hence, any surface defects on the flexible plate drastically reduce the fatigue life. This will lead to a fatigue failure that will cause catastrophic accidents and result in huge losses.

In the present work, a case study on surface defect at flexible plates of a HSFC has been carried out. A method of arresting fatigue crack on the surface of flexible plates has been studied and results are presented. The fatigue life of the flexible plates is improved by finding appropriate size and location of FCGA through finite element analysis and simulations.

2. HSFC and its Fatigue Failure

A schematic view of the HSFC is shown in Fig. 1. The flexible plate cross section may be straight, contoured, tapered or convoluted. The flexible plates are designed with variable thin cross-sectional thickness as shown in Fig. 2. Two flexible plate packs are connected to the input and output ends of HSFC by a centre tube to share the loads equally during operating condition. The flexible plate of a HSFC may have different types of surface defects including surface affected by weld spatter during electron beam welding, surface scratch or indentation due to mishandling during assembling.

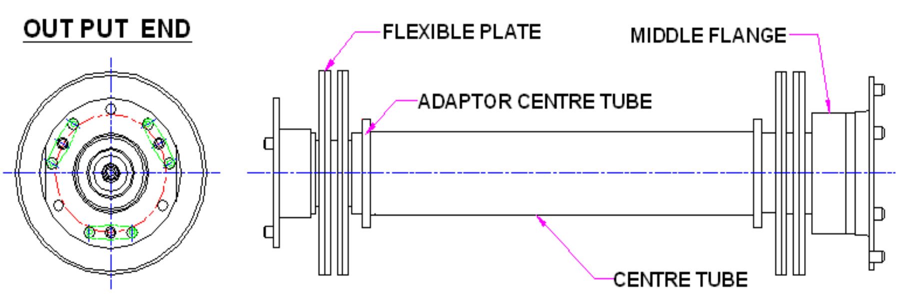

Fig. 1: Configuration of HSFC

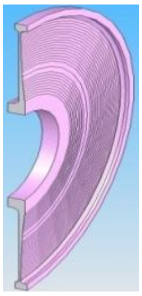

Fig. 2: Flexible plate section

The hot weld spatters on the surface of the flexible plates serve as multiple crack initiation sites [4]. The impregnation of molten alloy droplets in the form of spatters on the parent material causes the degradation of substrate material characteristics. The surface scratch or indentation on the flexible plates during manufacturing or handling during assembling is a cause of concern. These surface defects will lead to crack on the thinner cross section of the flexible plate. When a crack is present in a structure, it serves to concentrate local stress fields around its tip. As a result, the yield strength of the material can be exceeded around the crack to propagate the crack. If this propagation becomes self-sustaining or unstable, the structure will fail due to fracture. Such failure generally occurs due to applied stress perpendicular to the crack plane (Mode I) but other modes of failure such as in-plane shear (Mode II) and out-of-plane shear (Mode III) are possible [5].

Fig. 3 shows the premature failure of flexible plates of HSFC. As these HSFC assemblies are subjected to periodic examination, the presence of flaw can be easily detected. In order to arrest the propagating crack, it is prudent to consider a Fatigue Crack Growth Arrestor (FCGA) that will extend the service life of critical and costly HSFC.

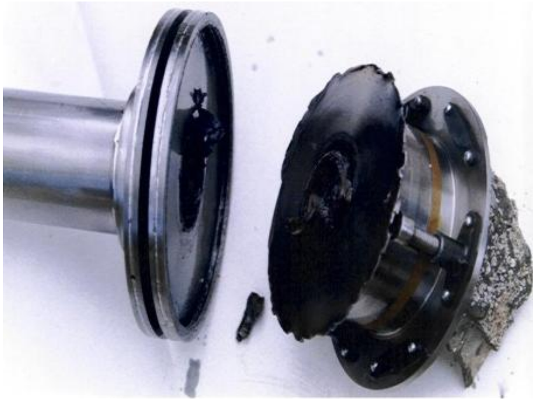

Fig. 3: Failure of HSFC

3. Sensitivity of Flaw on Flexible Plate

The HSFC assembly consists of four flexible plate packs. Two flexible plate packs at the input and output ends are required for HSFC to transmit the power. Each flexible plate shares the imposed misalignments. The flexible plates are made up of titanium alloy, 6Al-4V to the specification AMS 4928 [6]. The fatigue strength of titanium alloy 6Al-4V at room temperature is 450 MPa in solution treated and aged condition [7]. Table 1 shows the material properties of titanium alloy 6Al-4V [8].

Table 1: Material property of Ti 6Al 4V

Parameter	values	Unit
Density	4430	kg/m^3
Modulus of elasticity	113.6	GPa
Ultimate tensile strength	950	MPa
Yield strength	880	MPa
Rockwell hardness	36-38	HRc
Poisson’s ratio	0.346	-

The sensitivity analyses of the flawless and flawed flexible plates are carried out using commercial Finite Element Analysis (FEA) software – ANSYS version 11. The FEA technique is most suitable for analysing the annular flexible plates with varying cross sectional thickness [10]. The mesh generated for FEA is significantly denser in quality. Six tetrahedral type elements are used throughout the thicknesses of the flexible plate. This ensures bending stress and the distribution can be accurately resolved through the thickness of the part.

The equivalent misalignment imposed on a FE model of flexible plate is based on the maximum stress level of single flexible plate when HSFC is subjected to axial and lateral misalignments. The resulting stress level on a single flawless flexible plate with combined axial misalignment of 0.86 mm and lateral misalignment of 0.013 mm imposed is shown in Fig. 5.

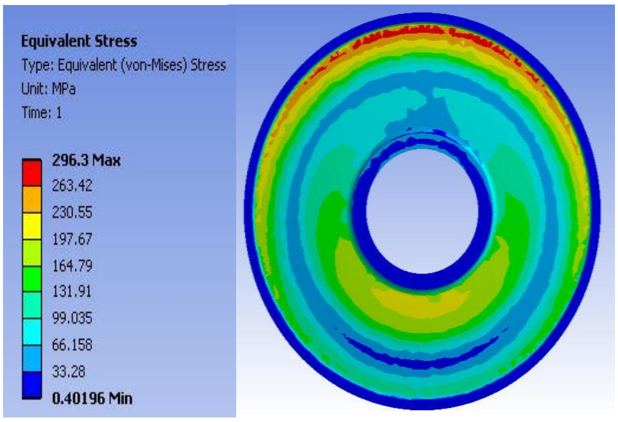

Fig. 5: Stress level on flawless flexible plate

With the specific specimen geometry and load case, it is possible to determine the sensitivity of initial flaw size on stress level on the flexible plate. The incipient flaws can be of different type, size orientation, morphology and location. A probabilistic methodology was proposed by Sankararaman et al [11] to estimate an equivalent initial flaw size distribution accounting for various sources of variability, uncertainty and error, for mechanical components with complicated geometry and multi-axial variable amplitude loading conditions.

The study of uncertainty in the flaw determination using statistical log-normal relationship between the measured and true flaw size based on the prior information of the flaw size and measurement results was undertaken by Ding Keqin [12]. The FEA of flexible plate with flaw located at top, middle and bottom position has been carried out. From the sensitivity analysis results as shown in Fig. 6, it is evident that incipient flaw is acting as a stress riser. For the imposed load, the stress level exceeds the material fatigue limit of 450 MPa.

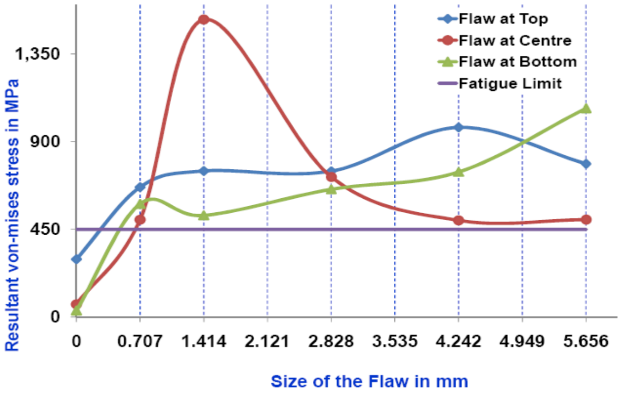

Fig. 6: Sensitivity of flaw on flexible plate

4. Design of FCGA

The fatigue behaviour of metallic materials has been summarised in numerous publications. It is generally agreed that the following four distinct phases of fatigue may occur [9]:

a) Nucleation;
b) Structurally dependent crack propagation (micro-structure short cracks phase);
c) Crack propagation that is described by either linear elastic, elastic-plastic or fully plastic fracture;
d) Final instability.

The fatigue of a component involves fatigue crack initiation and fatigue crack propagation. During high cycle fatigue regime, the crack initiation phase includes nucleation and propagation of micro-structure short cracks. Normally, it is assumed that approximately 90% of the total fatigue life is determined by the crack initiation phase. Additionally, the period of crack nucleation in smooth specimen without defects is assumed to be in the range of 5-20% of the fatigue life. The major part of the life is spent in the growth of micro-structure short cracks [9].

The problems of crack arrest and crack propagation are complex processes occurring in a micro second time interval with enormous velocities of crack propagation and pulse loading. To practically solve the problem of arresting a super-critical crack, either arresting crack itself or change in its trajectory to existing crack propagation along a safe trajectory can be adopted [9].

In the case of HSFC the following two methods of FCGA are considered:

1. Creation of extended elastic compression fields through mechanical means;
2. Blunting of the crack tip.

Considering a thin cross section of the flexible plates in the order of 500 microns, first method is not practical. In this work, second method is employed by drilling a hole at the crack tip to design a FCGA. A sudden increase in the radius of the crack tip causes a decrease in the stress concentration and thereby contains the blunted crack. To minimize the residual unbalance level of HSFC assembly, two holes are used as FCGA. These holes are drilled at equi-distance from center and positioned at 180 degrees as shown in Fig. 7.

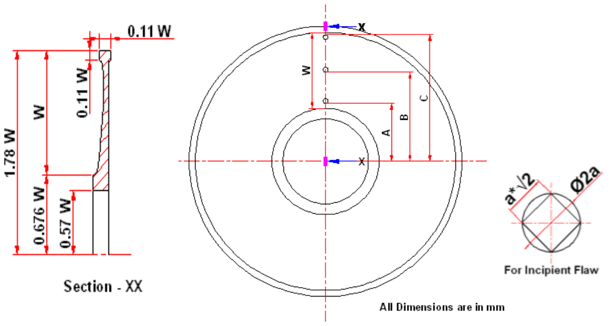

Fig. 7: Location of FCGA holes on the flexible plate

As the flaw can be of irregular shape, the maximum length of flaw oriented within a circular area is considered. With the size of incipient flaws, the size of FCGA has been determined. The length of the flaw is considered as the diameter (2R) of FCGA. The FCGA of '2a' mm diameter will accommodate the flaw within an area of square having a side of a*√2 where ‘a’ is the radius of FCGA. For the flaw of irregular shape, the maximum length of the flaw should be considered and diameter of FCGA will be more than the flaw length. For the location of FCGA, the working length (W) of flexible plate is divided into bottom (A), middle (B) and top (C) zones as given Table 3.

Table 3: Location of FCGA holes

Notation	Coordinates	Details of location
A	0.103W + R	Bottom
B	0.498W + R	Centre
C	0.976W - R	Top

5. Results and Discussions

FEA has been performed for flexible plate with various sizes of FCGA at different locations for combined axial and lateral load. The resulting stress distribution in flexible plate is shown in Fig. 8. The FCGA of 2 mm diameter that is located at the bottom location (A) of flexible plate gave a stress level below the fatigue limit (450 MPa). The stress distribution for this case (2mm FGCA) is shown in Fig. 9. The axial and lateral natural frequency of the HSFC has to be kept away from the operating range to avoid resonance. The variation in the axial and lateral spring rates will affect the dynamic characteristic of HSFC. Hence, the spring rate of the flexible plate with FCGA has been analysed.

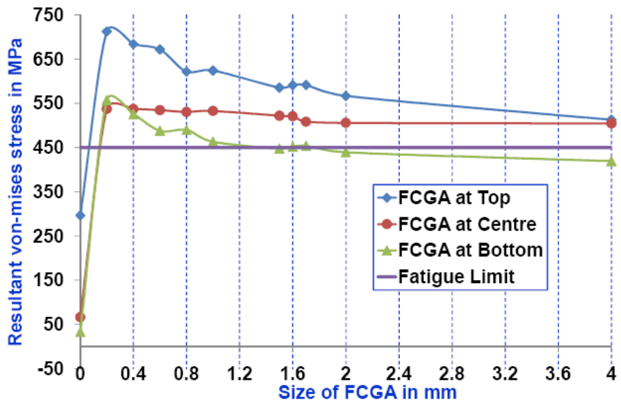

Fig. 8: Stress in flexible plate vs. Diameters of FCGA

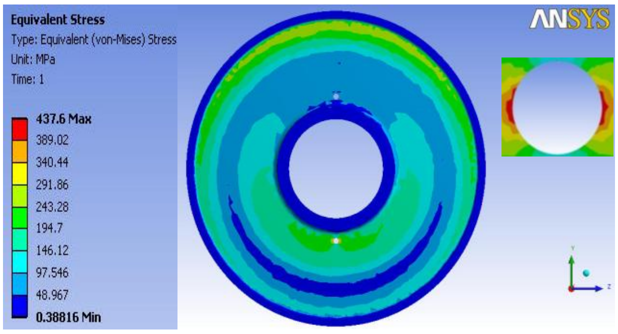

Fig. 9: Stress distribution of flexible plate with 2mm dia. FCGA

The spring rates are determined by linear static FE analysis. The axial spring rate of flexible plate with various sizes FCGA located at top, middle and bottom positions are shown in Fig. 10. For the applied axial load of 150N, the axial spring rate is found to be 172 N/mm for the flexible plate with FCGA of diameter 1.7 mm. For the FCGA of diameter 4 mm, it is observed that the reduction on axial spring rate is about 2.32% when compared with that of flawless flexible plate.

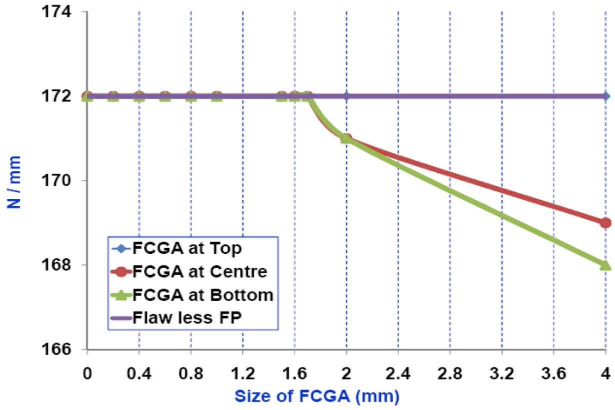

Fig 10: Axial spring rate of flexible plate with FCGA

The lateral spring rate of flexible plate with FCGA with various sizes located at top, middle and bottom positions are shown in Fig. 11. For the applied load of 10 N, the lateral spring rate is 12735 N mm/Deg for flexible plate with FCGA diameter of 2mm. The FEA results indicate that there is no change in the lateral spring rate of the flexible plate with FCGA for size up to 2mm at different locations. A marginal reduction of 1.02% in lateral spring rate for the FCGA size of 4mm (against flawless one) has been observed.

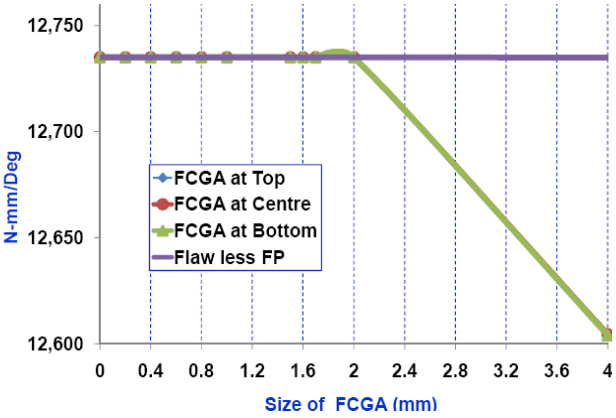

Fig. 11: Lateral spring rate of flexible plate with FCGA

Goodman stress based on a fully reversed load as given in Table 7 is considered to predict the fatigue life of flexible plates. Fatigue analyses are carried out for the following FE models:

- Flawless flexible plate;
- Flexible plate with incipient flaw of 1.414mm;
- Flexible plate with 1.414mm flaw and 2mm balanced FCGA located at the bottom of disc.

The combined axial and lateral misalignment was imposed on the FEA models. The fringe plot of fatigue life of flexible plate with 2mm FCGA is shown in Fig. 13. The predicted fatigue lives of the considered three cases are given in Table 8. From the results, it can be evident that the fatigue life of flawed plate with FGCA has been improved by ~18% against flawed plate.

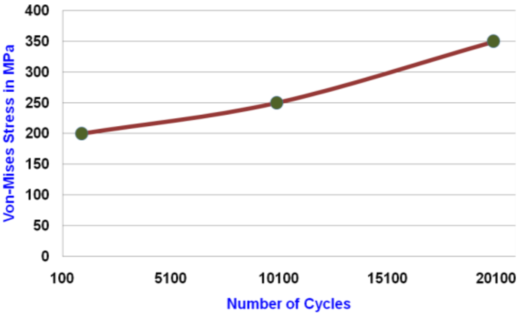

Fig. 13: Goodman stress vs. Cycles for fatigue analysis

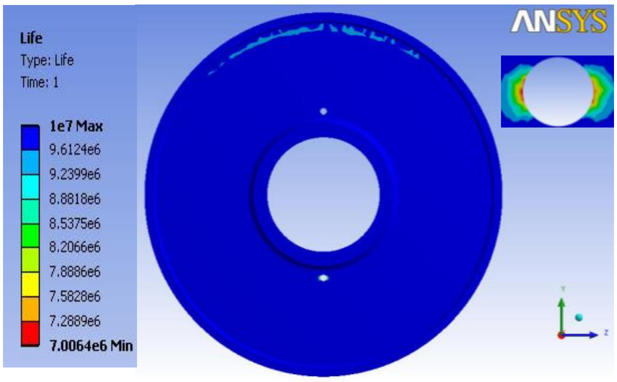

Fig. 13: Fatigue life of flexible plate with 2mm FCGA

Table 8: Fatigue analysis results of flexible plate

Flexible plate	Fatigue life in million cycles
Flawless	9.2877
With flaw only	5.7437
With flaw and FCGA	7.0064

6. Conclusions

The sensitivity analysis of a flexible plate used in HSFC in the form of flawless and with incipient flaw located at top, middle and bottom position has been carried out with extreme misalignment conditions. The results indicates that the flexible plate with FCGA up to 4 mm diameter located at top and centre positions generate stresses which are above the fatigue limit of 450 MPa and a reduction of 2.32% in axial spring rate of HSFC. It is also observed that there is no change in the lateral spring rate of the flexible plate with FCGA of size up to 2 mm at different locations and marginal reduction of 1.02% in lateral spring rate for the FCGA sizes between 2 mm and 4 mm.

The FEA on fatigue life-cycle indicates that with the adaptation of FCGA size of 2 mm diameter, an improvement of 18.02 % in fatigue life cycles is achieved when compared to a flawed flexible plate. For the present work, it is concluded that the flexible plates with FCGA of 2 mm diameter can be used as a fatigue arrester for a flaw size of 1.414mm under combined axial and lateral loading. The surface flaws attributed during machining or mishandling of the HSFC can be overcome by the adaptation of the proposed FCGA.

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