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Importance of Fatigue Life in Design Optimisation of Off-highway Powershift Transmission system

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Abstract

Life time of off-highway vehicle is mostly determined by the fatigue life of its components. Variability in the design and material parameters has vital effect on the fatigue life. In order to achieve better performances together with improved safety, a new design process is needed to build powershift transmission components. The new process requires shift from traditional design approach to new approach that incorporates all the variability and uncertainties in the analysis phases as well as in the design flow with the help of computer simulation methods to guarantee design reliability. Present work deals with the importance of fatigue life in design optimization of off-highway vehicle transmission housings and the methods to calculate the fatigue life of the housings. Design parameters have been optimized on the basis of the components life. Traditional design involves the calculation of static stress limit for the material stress values with higher factor of safety. Due to higher factor of safety, cost of the components goes up by means of the various design features like increased wall thickness, oversized fillets and ribs, etc. Transmission housings experience variable loadings with respect to the working environments. These variable loadings affect the component life abnormally, which may cause the damage of transmission components within the defined life cycle. To enhance the product performance, fatigue life of the transmission housing has been predicted and design has been optimized to reduce the component cost.

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Introduction

Present market demands low cost and light weight vehicle component to meet the need of fuel efficient and cost effective vehicle. Reducing weight gives multi-disciplinary challenges such as stiffness, strength, fatigue life, etc[1]. Off-highway vehicle are used for cyclic operation on an off-road, therefore many components or structures always suffer fluctuating load, which is sometimes small, but they result in the potential danger, since it can make the component to break suddenly without any apparent indication. The failure of components under fluctuating (cyclic) load is called fatigue which plays important role in design of off-highway powershift transmission system. Powershift transmission system is mounted on vehicle chassis along with engine, hence transmission housing experiences fluctuating load from engine as well as from the vehicle. Stress optimised shapes may not be optimal from the fatigue stand point therefore prediction of fatigue performance of the housing structure is prime importance. Fatigue cracks originate mostly from the surface, as the stresses due to loads (such as bending and torsion) are generally high at the surface compared to the inside material[2]. The fatigue resistance of sub-surface material is also higher (approximately by 1.4 times) than that of the surface[3]. Besides, the surfaces are subjected to machining and handling defects which act as stress raisers. These machining operations induce residual stresses that can adversely affect the fatigue response and even the dimensional stability as well as further machining. It is always a challenge to the designer to maximize the fatigue strength without any additional weight or cost increase.

This paper describes how to achieve weight or mass reduction of powershift transmission housing assembly under fatigue loading using FEA by topological optimization method. Reduction of component mass will not only save cost, but also improves vehicle fuel efficiency due to lesser energy requirement to move a lighter vehicle. Therefore, weight reduction will contribute towards saving costs as well as environmental sustainability. The fatigue life prediction using FEA consists of four primary steps. First a theoretical or constitutive equation, which forms the basis for modelling, is either defined or chosen. Appropriate assumptions need to be made in constructing the constitutive equation. Second, the constitutive equation is translated into FEA program and a model is created. The FEA program calculates the predicted stress-strain values for the system under study and returns stress values for the simulated conditions. Third, the FEA results are used to create a model predicting the number of cycles to failure. Fourth, the model or results must be tested and verified by measurement data.

Many technical papers have been dealing with fatigue life predictions of different components such as Engines, driveline, vehicle body using different methods ranging from finite element analysis to fracture mechanics theories that are mainly based on destructive testing. For example, *Buciumeanu et al.*[4] designed suspension component by taking into account fatigue requirements. *Lee et al*.[5] optimized a connecting rod subjected to a certain fatigue life. The aim of this work is to study and review various techniques of fatigue life calculations and their applications in design optimisation of powershift transmission housing.

Methodology for Housing Design Optimisation

The design optimisation techniques used in industries, require the product performance improvement and cost benefits. Optimization indicates to make the structure as light as possible, as stiff as possible and as an insensitive to improve life as possible

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with demanded. Most of the physical parameters that can be set as constraints could also be used as objective functions. By choosing a plenty of measures on structural performance—weight, stiffness, critical load, stress, fatigue life, displacement and geometry, a structural optimization problem can be formulated by picking one of these as an objective function that should be maximized or minimized and using some of the other measures as constraints.

Objective function: A function that should be maximized or minimized and during every optimization iteration, function returns a value which indicates the quality of design. Choosing the objective function is a crucial part of the optimization process, in general objective could be weight reduction, displacement in a given direction, effective stress or even cost of production[6].

Design variable: A function or vector describing the geometry or choice of material and allowed to change in order to minimize the objective function. If design variables refer to geometry, it could be the cross section area of material or the wall thickness of housings[6].

State variable: A function or vector representing the response with given design variables of a structure when acted on by certain load. For a mechanical structure, variable may indicate displacement, stress, and Fatigue life[6].

The powershift transmission design is complicated towards its application in a defined working environment. The housing of powershift transmission holds many subsystems and parts like Gears, shafts, bearing, clutches, torque convertors, and hydraulic components which are critical for the housing fatigue life. All the internal parts are very much related to the housing design in the following context:

1. Bearing placement or location.
2. Gear type and arrangement.
3. Gear and shaft loads.
4. Clutch and hydraulic loads.
5. Housing mounting to the vehicle frame.
6. Housing coupling with the engine.
7. Mechanical environment like external loads.

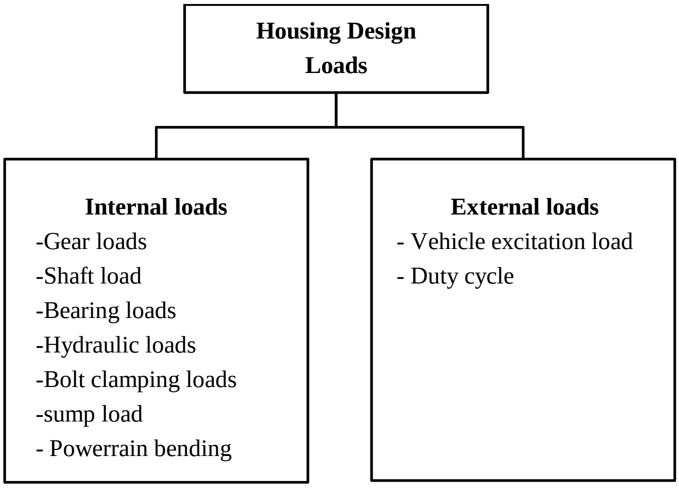


Figure 1: Loads considered in housing design

The powershift transmission housing loads are generally classified as internal loads and external load as shown in the Fig. 1.

Traditional Housing Design method: The traditional method of doing the housing design optimization is to follow the material strength up to operating strength and finding out the factor of safety. This is being done by the hand calculations or the simple FEA methods to calculate the Stress and deflections. Here, there is no focus on the transmission Fatigue life. Initially, the internal components like gears, shaft and clutch arrangement will be finalised and then housing design will be constructed to hold the internal parts called as torque transfer systems in the powershift transmission. Fig. 2 explains the general design calculation and their methodology to finalise the housing design layout.

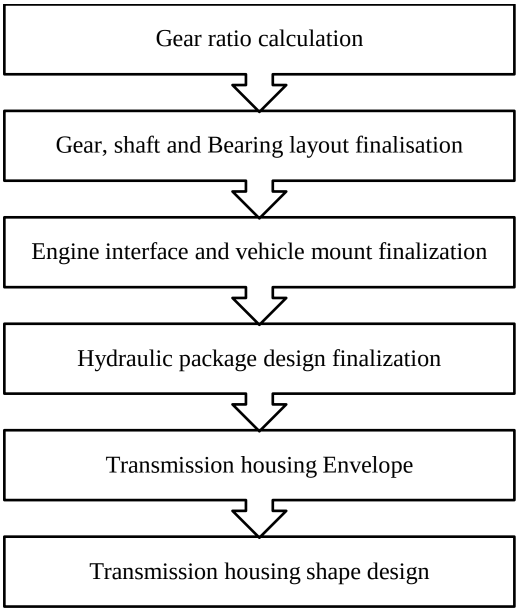


Figure 2: Housing design process

Transmission housing layout design basically starts from the gear design layout to its 3D CAD modelling stage which is explained in Fig. 2. The finite element methods are very much available for doing the stress calculation of any mechanical / structural design. Fig. 3 shows the traditional method of housing optimisation which involves the calculation of stress and deflection.

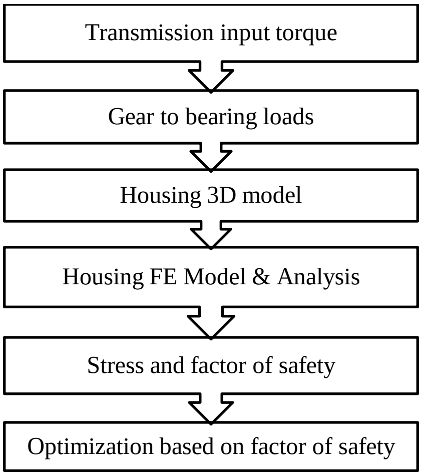


Figure 3: Traditional method of housing optimisation

As discussed in the previous topics, various loads are needed to be considered in finite element load application and boundary conditions.

While doing the transmission housing optimisation from the above said methodology as traditional methods, the factor of safety will be decided based on the housing material strength. In this case, optimisation is the function of material strength and Operating loads which is shown in equation 1.

$$Housing\ Optimisation\ = f\ (S_m, L_o) \qquad (1)$$

$where, S_m$ $-$ $Material\ strength\ for\ static$

L_o $-$ $Operating\ loads$

Increased factor of safety in the stress analysis leads to higher material addition to the housing design. Higher factor of safety gives enough strength to housing to withstand higher loads but on the other hand it is increasing the cost of the overall product and thereby increasing complication on design outcomes. The important point needs to be explored is to provide sufficient material and stiffness to the required area and avoid unwanted materials. The approximate factor of safety method is not a suitable method to finalise and conclude the design of powershift transmission housing.

Vehicle load is demanding more robust design of subsystems level, that is when the importance of optimisation coming into the design phase. Finite element analysis method, used for the calculation of stress and deflection with respect to the load calculated by gear and bearing arrangement, optimizes the housing design based on the review of stress plot, but it is not sufficient to account for the fatigue load since the transmission receives the variable loads from the vehicle duty cycle.

Following are the disadvantages of traditional design method:

1. Increase material or wall thickness in the transmission housing design.
2. Improper shape design limited to static stress.
3. Over strength material consideration.
4. Focus on concentrated steady loads only.
5. No conformity ton housing fatigue life.

Therefore, a need of considering fatigue life calculation in housing design is required because transmission takes cyclic load that even varies in the time domain based on the vehicle duty cycle.

New Design Optimisation methodology

Effective transmission housing optimisation involves various approaches which deals with vehicle loads, transmission internal loads as discussed. Important criteria for the effective optimisation are fatigue life calculation using FEA methods. The method of new design analysis and its optimisation is shown in Fig. 4. This is explained using one of the powershift transmissions housing design optimisation.

Fatigue theory and Review mechanism

Fatigue cracks are caused by the repeated application of loads which individually would be too small to cause failure. Fatigue cracks usually initiate from surface of the component. This is a crack initiation. The crack may then propagate in a direction perpendicular to the direct stress. This is crack propagation. Finally the component may fracture. Modern fatigue theories provide separate analysis for each phase[7]. The phases are shown in the Fig. 5.

Crack initiation theories are based on assumption that fatigue cracks are initiated by the local strains and stresses on the surface of a component. Crack propagation theories relate crack growth to the stress in the component. Fatigue analysis tool is helpful in predicting crack initiation spot. Final fracture is analysed using fracture mechanics. Earlier theories treated the whole of the fatigue life as a single entity, and related fatigue life to the calculated engineering stress in the component. Most of current research is attempting to describe the whole fatigue process by the study of crack propagation from very small initial defects. The simplest form of stress spectrum to which a structural element may be subjected is a sinusoidal or constant amplitude stress-time history with a constant mean load[7], as illustrated in Fig. 6.

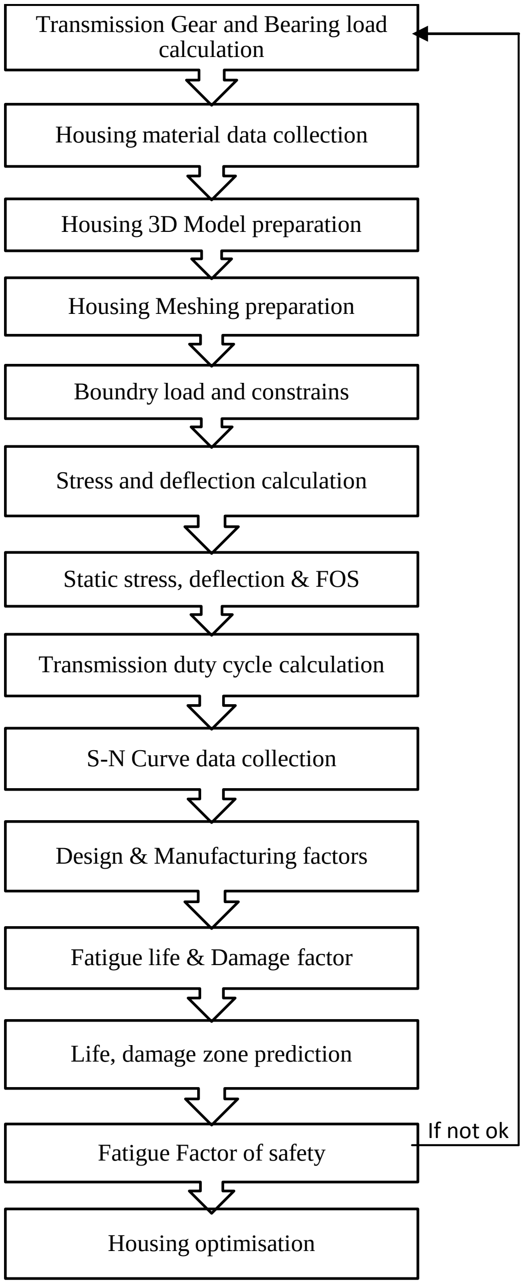


Figure 4: New methodology of housing optimisation

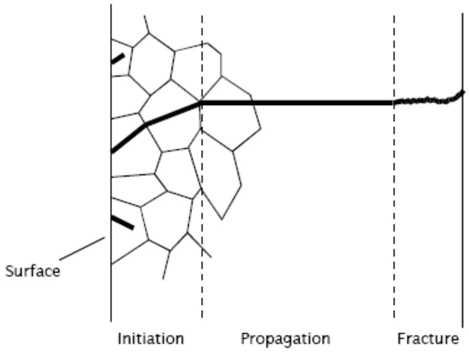


Figure 5: Three stages of fatigue failure

Since this is a loading pattern which is easily defined and simple to reproduce in the laboratory it forms the basis for most fatigue tests. The following six parameters are used to define a constant amplitude stress cycle[7].

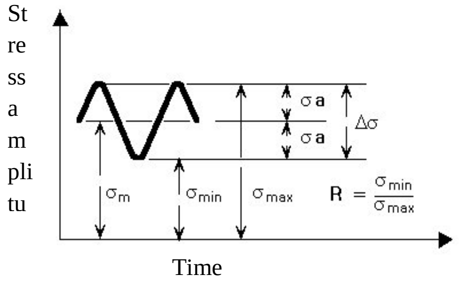


Figure 6: Stress amplitude fatigue loading

σ_{max} = maximum stress in the cycle
σ_{min} = minimum stress in the cycle
σ_m = mean stress in the cycle = $(\sigma_{max} + \sigma_{min})/2$
σ_a = stress amplitude = $(\sigma_{max} - \sigma_{min})/2$
$\Delta\sigma$ = stress range = $\sigma_{max} - \sigma_{min} = 2\sigma_a$
R = stress ratio = $\sigma_{min}/\sigma_{max}$

The first step of the fatigue analysis is the superposition of all the loading and stress outcomes from the static analysis. The stress results are for every load of the finite element analysis over the time span with respect to the Transmission duty cycle. The fatigue analysis have separate flow with software starting from stress analysis input to Fatigue analysis process which is having Material properties, S-N curve, duty cycle conversion to time history curves.

S-N theory deals with uniaxial stress. The Von-misses stress on the stress components was used to look up for damage on S-N curve. The S-N curve provides a relationship between the fatigue strength ('S' or s) and the fatigue life ('N') which can be described as[7],

$$\frac{N}{N_D} = \left[\frac{\sigma}{\sigma_d}\right]^K \qquad (2)$$

Where N_D is the fatigue limit cycles, σ_d the endurance limit and k the slope of S-N curve. The *Gerber* criterion is used as mean stress corrections.

The damage Di is given by the relationship between the cycle n and the fatigue limit cycle N at the same stress amplitude i

$$D_i = \frac{n_i}{N_i} \qquad (3)$$

To obtain the damage for a load case with different stress amplitudes over the time, the linear damage accumulation[7] by *Pilmgreen-Miner* can be used as follows,

$$D_i = \sum_{i=1}^{n} \frac{n_i}{N_i} \qquad (4)$$

A fatigue analysis based on finite element method calculates damages for the transmission housings parts of the finite element mesh. The result can be used as an objective function in the shape optimization. Housing assembly material (SAE G2500) details and S-N curve for that material[8] are shown in Table 1 and Fig. 7 respectively. In this analysis a load case was applied from duty cycle as shown in Table 2. The lower bound of fatigue life is constrained according to vehicle the duty cycle and field validation data.

Table 1: Material properties for SAE G2500

Material	SAE G2500
Density	7.42 E-6 kg/mm3
Poisson's Ratio	0.26
Modulus of elasticity	200 GPa
Ultimate tensile stress	169 MPA

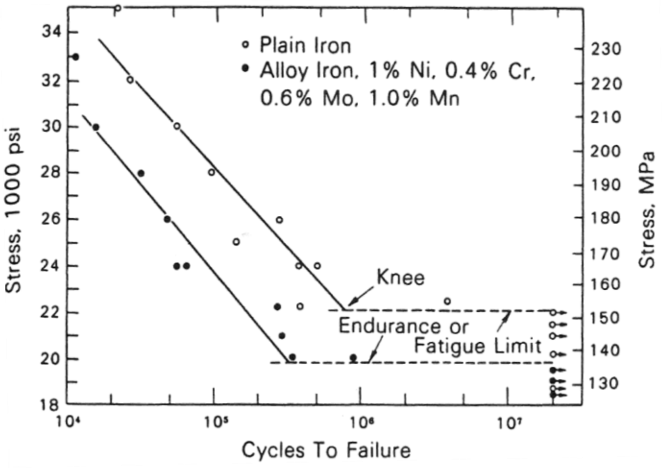


Figure 7: S-N curve for SAE G2500 Grey Iron Cast

Using a shape / topological optimization based on finite element results, material and shape of the housing of finite element mesh are optimization variables[9]. The objective function of a shape optimization based on fatigue analysis is maximum damage in the design space. A constraint on the volume can be used. The easiest way is a reduction of the damage with the same material. Sometimes it is also possible to reduce the used volume. Other constraints such as a constant displacement between two variables, a limited maximum stress in the whole structure, or a limitation of the design space, may also be possible[10].

The fatigue failure is related to the surface factor which will deal with the crack initiation and growth, hence machined surface finish is considered[7] (Kt =1.3 as shown in Fig. 8). This is important while considering the fatigue analysis for any machined transmission housing.

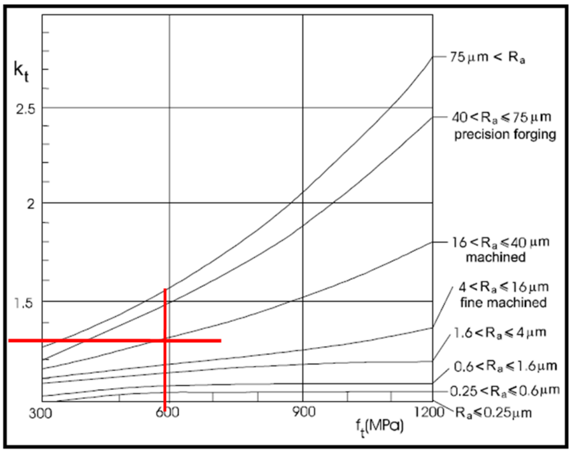


Figure 8: Surface finish factor (Kt)

Fatigue design and analysis methodology

Different fatigue analysis methods and software are available to validate the transmission housing design. All those methods are having some constraints and some advantages. Process for the fatigue analysis and utilising the fatigue analysis is very important for the transmission optimisation. The below Fig. 9 shows the simple process for the fatigue analysis with FEA software.

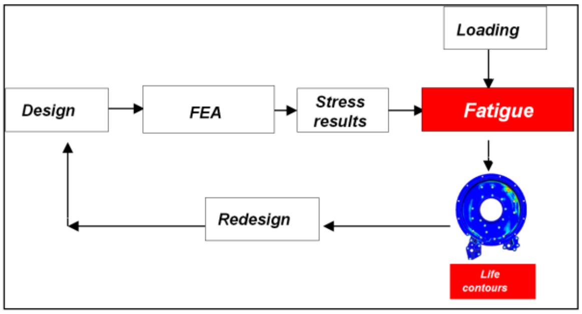


Figure 9: Routing of Fatigue analysis

Transmission housing assembly has 3 parts like convertor housing, front housing and rear housing. Fatigue life of each components are calculated as follows;

1. Stress tensors are multiplied by the time history of the applied loading, to produce a time history of each 6 components of stress tensor.
2. Time histories of in-plane principal stresses are calculated.
3. Time histories of 3 principal strains are calculated from stresses.
4. Multi-axial cyclic plasticity model is used to convert elastic stress-strain histories in to elastic plastic stress-strain histories.
5. Critical plane method is used to identify most damaging plane.
6. For each of the critical planes, strains are resolved on to 3 shear planes.
7. Time history of damage parameter is counted.
8. Individual fatigue cycles are identified, fatigue damage for each cycle is calculated and total damage is summed.
9. Plane with shortest life defines the plane of crack initiation.

The stress data for all the load cases are fed to the fatigue software. The number of cycles is repeated for each loading as shown in the table 2. The transmission has multi speed gear shift having forward / reverse and working environment is off-road condition with various duties like travel, loading and dozing. The torque and the speed of the transmission have been measured with respect to the gear shift speed and time taken for the each operation. These complete set of transmission duty cycle is repeated to predict the life of the powershift transmission housing assembly.

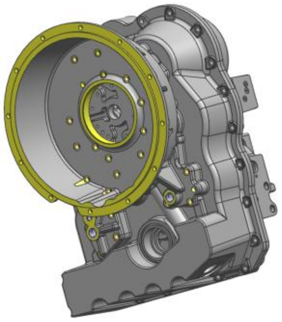


Figure 10: 3D model of powershift transmission housing

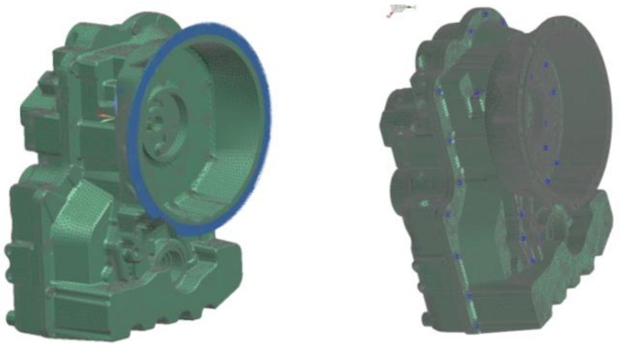
Table 2: Transmission Duty cycle

Transmission duty cycle							
Condition	Time %	Gear shift	Duration (Sec)	Transmission Input Torque (N.m)	Transmission Output Torque (N.m)	Transmission Input Speed (rpm)	Transmission Output Speed (rpm)
1	6	1 Fwd	0	645	3,181	0	0
2	2.5		0.1	600	2,960	201	40
3	3.5		0.2	548	2,703	402	81
4	3.3		0.3	499	2,463	603	122
5	3	1 Fwd	0	645	3,181	0	0
6	3		0.2	548	2,703	402	81
7	3		0.3	499	2,463	603	122
8	3		0.4	446	2,201	804	163
9	3	2 Fwd	0.3	499	1,339	603	224
10	2.4		0.4	446	1,196	804	299
11	2.5		0.5	400	1,074	1,005	374
12	3	3 Fwd	0.4	446	578	804	620
13	2.4		0.5	400	519	1,005	776
14	2.4		0.7	304	394	1,477	1140
15	3	1 Rev	0.1	600	2340	201	51
16	2.4		0.2	548	2,138	402	103
17	1.8		0.3	499	1,948	603	154
18	1.8		0.4	446	1,740	804	206
19	2.2	2 Rev	0.3	499	1,059	603	284
20	1.5		0.4	446	946	804	379
21	1.5		0.5	400	849	1,005	474
22	2.4	1 Fwd	0	645	3,181	0	0
23	1.8		0.2	548	2,703	402	81
24	1.5		0.4	446	2,201	804	163
25	1.2	2 Fwd	0.3	499	1,339	603	224
26	0.9		0.4	446	1,196	804	299
27	0.9		0.5	400	1,074	1,005	374
28	0.9	3 Fwd	0.5	400	519	1,005	776
29	0.9		0.7	304	394	1,477	1140
30	0.9	4 Fwd	0.7	304	214	1,477	2,098
31	0.9		0.8	217	153	1,764	2,505
32	2.5	1 Rev	0.2	548	2,138	402	103
33	1.8		0.3	499	1,948	603	154
34	1.8		0.4	446	1,740	804	206
35	1.5	2 Rev	0.3	499	1,059	603	284
36	0.9		0.4	446	946	804	379
37	0.9		0.5	400	849	1,005	474
38	1.2	1 Fwd	0.2	548	2,703	402	81
39	1.5		0.3	499	2,463	603	122
40	1.8		0.4	446	2,201	804	163
41	2.4	2 Fwd	0.4	446	1,196	804	299
42	3.5		0.5	400	1,024	1,005	374
43	2.8	3 Fwd	0.5	400	519	1,005	776
44	3.7		0.7	304	394	1,477	1140
45	4.2	4 Fwd	0.8	217	153	1,764	2,505

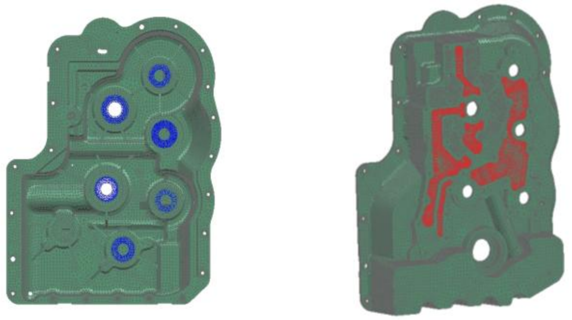
The 3D model of the power shift transmission assembly is shown in Fig. 10. Finite element model for transmission housing assembly is shown in Fig. 11(a). In the FEA analysis all the loads and boundary conditions are applied. The boundary condition represented to real transmission working condition with vehicle.

Load and constraints: The power shift transmission convertor housing flange face is mounted with engine by means of bolts. So the flanges and bolt holes are constrained in FEA as shown the Fig. 11(a) & (b). All the gear loads are calculated based on the input torque for each gear shift conditions and then bearing reaction loads are calculated to apply loads on the FE mesh model as shown the Fig. 11(c).

The power shift transmission is a combination of mechanical, hydraulic and electrical systems. The hydraulic is the medium of transmission controls which is operating the clutch engagement between one gears to another gear. The hydraulic oil passages are integrated with housing to give sufficient pressure to the clutch systems. The pressure applied to the housing FEA model as shown the Fig. 11(d).



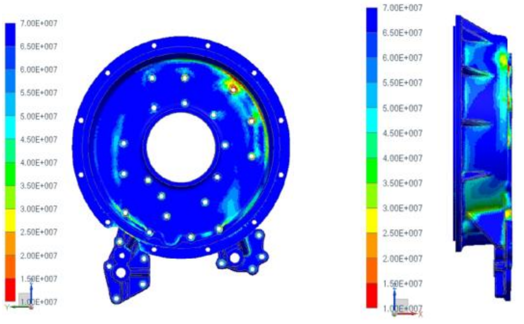
(a). Mesh with flange mounting **(b).** Mesh with bolt constrains



(c). Mesh with Bearing loads **(d).** Mesh with Hydraulic loads

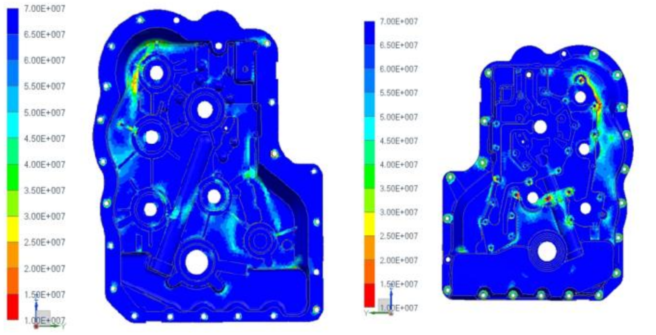
Figure 11: Transmission housing loading and constrains

The stress analysis is conducted and the results of all the load cases have been reviewed and accounted for the fatigue load case using the material S – N curve and transmission duty cycle. Fig. 12, 13, 14 & 15 shows first level fatigue results of the transmission components. The zones which are highlighted hot spots (in the red colour) have minimum fatigue life and hot spot of the housing fatigue pattern which is called as damage zones for converter housing, front housing and rear housing as shown the Fig. 12, 13, & 14 respectively. Low fatigue life zones have been carefully reviewed and taken for the second level of housing assembly modification and the same flow of FEA has been followed and fatigue analysis is carried out for optimisation.



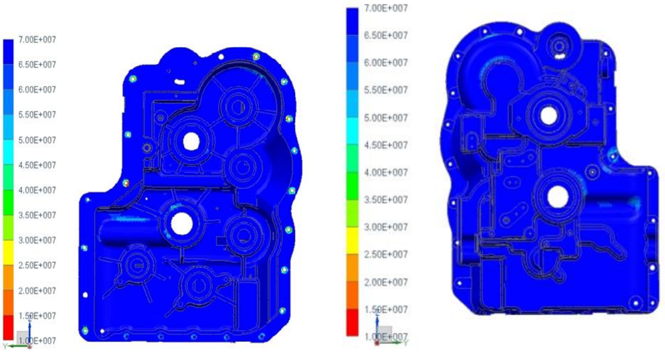
Converter fatigue life - plot 1 Converter fatigue life - plot 2

Figure 12: First stage Converter housing fatigue life



Front housing fatigue life - plot 1 Front housing fatigue life - plot 2

Figure 13: First stage front housing fatigue life



Rear housing fatigue life - plot 1 Rear housing fatigue life - plot 2

Figure 14: First stage rear housing fatigue life

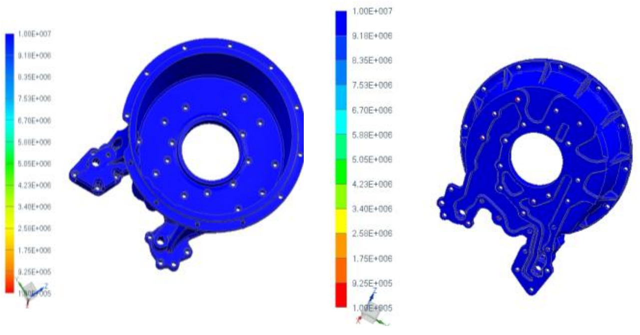
Similarly, third & fourth stage of modification and FEA iterations are conducted and the low fatigue zones have been analysed. Housing components with improved fatigue life as well as optimised weight along with improved damage zone by eliminating the stress contribution on the housing hot spot area of converter housing, front housing and rear housing are shown in the Fig. 15, 16, & 17 respectively. The transmission duty cycle is well utilised with fatigue life calculation and integrated with fatigue analysis of the powershift transmission system.

The new method of powershift transmission optimisation is very well interpreted with multi stage optimisation and that describes the optimisation of transmission housing is the function of Material strength of static, operating loads, fatigue material data, machining factor and vehicle duty cycle which is shown in equation 5.

$$\text{Housing optimisation} = f\left(\mathrm{S_m}, \mathrm{L_{o,}} \mathrm{M_{f,}}, \mathrm{F_{m,}} \mathrm{D_{v,}}\right) \qquad (5)$$

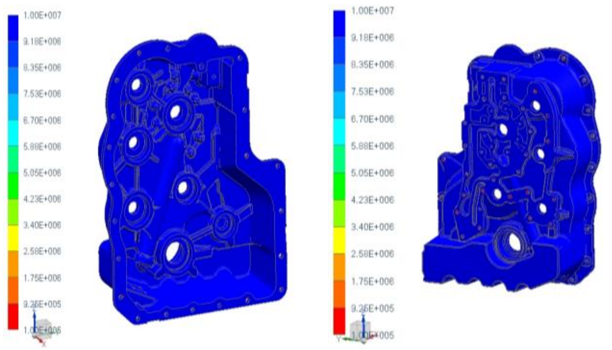
$where, S_m$ $-$ $Material\ strength\ for\ static$
L_o $-$ $Operating\ loads$
M_f $-$ $Fatigue\ material\ data$
F_m $-$ $Machining\ factor$
D_v $-$ $Vehicle\ duty\ cycle$

Initial design of the transmission housings assembly has total weight of 178 kg. Figure 18 shows weight reduction of each housing at different stages of optimisation. After fourth stage of optimization, final weight of the housings assembly is 151 kg. Two of the components, front housing and rear housing weight have been reduced almost by 20 % whereas the converter housing demanded more material to withstand fatigue strength, so it is increased by about 10 % as shown in Fig. 18.



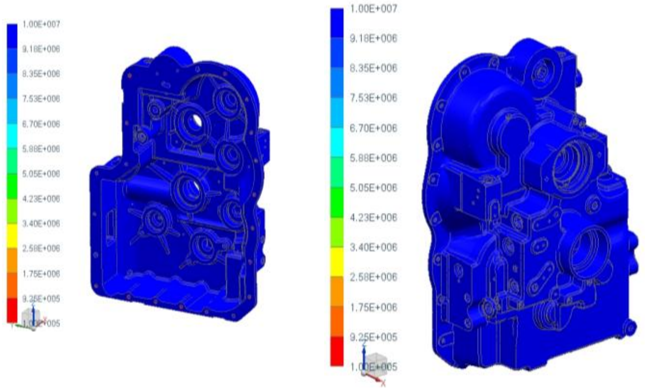
Converter fatigue life - plot 1 Converter fatigue life - plot 2

Figure 15: Fourth stage converter housing fatigue life



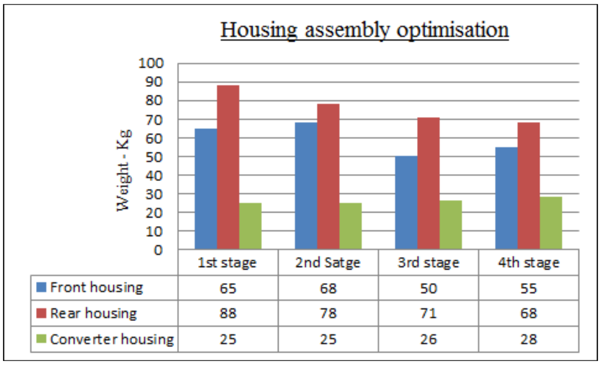
Front housing fatigue life - plot 1 Front housing fatigue life - plot 2

Figure 16: Fourth stage front housing fatigue life



Rear housing fatigue life plot 1 Rear housing fatigue life plot 2

Figure 17: Fourth stage rear housing for fatigue life



	1st stage	2nd Satge	3rd stage	4th stage
🟦 Front housing	65	68	50	55
🟥 Rear housing	88	78	71	68
🟩 Converter housing	25	25	26	28

Figure 18: Weight reduction in different stages of housing optimisation

Conclusion

The powershift transmission housing weight has been optimised using the fatigue life analysis approach which was not explored in the traditional method. This in turn reduced the component cost and vehicle performance has been enhanced. It is found that new method of optimisation is the function of material strength, operating loads, fatigue properties, machining factor and vehicle duty cycle. The approach explained in this study can be applied to other vehicle components to enhance the overall performance of vehicle at reduced cost.

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