Periodica Polytechnica Transportation Engineering

47(1), pp. 68-81, 2019
https://doi.org/10.3311/PPtr.10188

RESEARCH ARTICLE

Twin Shaft-Geared Crankweb Crankshaft System with Optimization of Crankshaft Dimensions Using Integrated Artificial Neural Network-Multi Objective Genetic Algorithm

Anierudh Vishwanathan[1*]

Received 18 October 2016; accepted 19 January 2017

Abstract
This paper suggests a novel design of a multi cylinder internal combustion engine crankshaft which will convert the unnecessary/extra torque provided by the engine into speed of the vehicle. Transmission gear design has been incorporated with crankshaft design to enable the vehicle attain same speed and torque at lower R.P.M resulting in improved fuel economy provided the operating power remains same. This paper also depicts the reduction in the fuel consumption of the engine due to the proposed design of the crankshaft system. In order to accommodate the wear and tear of the crankshaft due to the gearing action, design parameters like crankpin diameter, journal bearing diameter, crankpin fillet radii and journal bearing fillet radii have been optimized for output parameters like stress which has been calculated using finite element analysis with ANSYS Mechanical APDL and minimum volume using integrated Artificial Neural Network-Multi objective genetic algorithm. The data set for the optimization process has been generated using Latin Hypercube Sampling technique.

Keywords
modified crankshaft, twin shaft, engine revving, Artificial Neural Network, optimisation

[1] Department of Mechanical Engineering,
BITS, Pilani,
Pilani Campus, Rajasthan, India, 333031
Researcher ID: 2013ABPS625P
[*] Corresponding author, e-mail: anierudh223@gmail.com

1 Introduction

Diesel engines have a wide range of applications in both small and large vehicles. Ever increasing environment concerns, the escalating number of stringent norms along with rising requirements for improved performance, fuel economy and economic feasibility makes it inevitable for researchers to develop novel and optimized technologies to improve fuel economy, performance and reduce emissions thereby meeting the challenges posed by the automotive industry. Stiff competition from the hybrid vehicles further necessitates integration of fuel saving technologies into the diesel engines. Crankshaft is one of the most crucial components of any internal combustion engine which converts rotary motion into reciprocatory motion using a four link mechanism hence design developments in this field are crucial to the automotive industry. They can be classified as built-up type crankshafts operating in two-cylinder engines and solid type crankshafts operating in four stroke engines. Crankshaft is a complex system involving several variables and mathematical equations to be taken into consideration in its design. Therefore, there lies tremendous scope in exploiting the crankshaft design to improve the fuel economy of the engine.

Extensive research has been conducted to explore the possibilities of using biofuels as an alternative to fossil fuels to curb emissions while maintaining the same performance of the engine (Lapuerta et al., 2008). Quantitative analysis has been done to analyse the commercial potential of using biodiesel in vehicles. Policy incentives for manufacturers and users of biodiesels have also been presented (Demirbas, 2007; Agarwal, 2007). Hybrid technology is another area in which thorough studies and experiments have been conducted to reduce the emissions and increase fuel efficiency of the IC engine. Issues like energy conversion efficiency of the hybrid engines have been documented (Katrasnik, 2007). Use of pneumatic power systems to recycle and store waste heat into mechanical energy has been suggested and verified using computer simulations (Huang, 2005). Hybrid drivetrains and telematics technologies have been compared on the basis of the improvement in the fuel economy relative to the baseline vehicle (Manzie, 2007). Fuel efficiency can be further improved by integrating an electric motor with the IC engine (Huang and Tzeng, 2004). Hydrogen energy is another thrust area in which extensive research has been conducted for reducing emissions and improving fuel economy of spark ignition engines (Ma and Wang, 2008; Akansu et al., 2004; AlBaghdadi et al., 2000; Ma et al., 2007). Thorough studies pertaining to the effects of hydrogen, hydrogen-ethyl alcohol additives on closed cycle variation, engine performance and emission characteristics in a four stroke spark ignition engine have been carried out. Comparisons between CNG and H/CNG have been documented (Ma et al., 2008). Literature pertaining to the tribological advancements for emission reduction is also significant. Tribological Nano coatings using plasma technology processes on engine components have been employed and improvement in the fuel efficiency has been reported (Vetter et al., 2005). Tribological significance of major frictional components in an engine has also been documented and it has been proved that combined application of surface treatment and decrease in lubricant viscosity can improve fuel economy by over 4% (Taylor, 1998; Fox, 2005). There have been significant advancements in improving the fuel efficiency of the engine by varying burn duration, combustion phasing and load by turbocharging, varying spark timing and unburned temperature (Olesky et al., 2013). A two-zone engine thermodynamic model has also been developed to study the characteristics in an IC engine (Rakopoulos et al., 2009). Several functioning parameters of other engine components have been varied to obtain an improved fuel efficiency of the engine. Modification of the slider crank mechanism, addition of an eccentric connector between connecting rod and crankpin, variation of valve timings to control the engine load, dynamic optimization of a mean value model comprising of two state variables namely intake manifold and engine speed represent some of the ways to improve the fuel efficiency and reduce (Fontana and Galloni, 2009; Erkaya et al., 2007; Saerens et al., 2009). Two-step surface response methodology based engine optimization, variation of spark timings and unburned gasoline temperatures have resulted in fuel economy improvement (Molina et al., 2014; Olesky et al., 2013). Research has been conducted to develop a two-cylinder gamma type low temperature differential engine operating on Stirling cycle; various parameters have been compared with that of a diesel engine (Tavakolpour et al., 2008). A pure ethanol engine has also been designed using fast actuating high pressure fuel direct injection, high boost turbo charging and fully variable valve actuation. BSFC and fuel economy have been calculated using vehicle simulation packages (Boretti, 2012). Two stage premixed combustion (Low temperature and high temperature) using relatively low-reactivity and high volatility fuel is uncovered in the MPCI mode, it has been concluded that the temporally and spatially distributed combustion in MPCI mode decreases the local temperature, resulting in less NOx formation and lower heat transfer. (Yang et al., 2015). Novel design of a variable compression ratio advanced spark ignition engine which will allow an expansion ratio that may differ from the compression ratio hence will generate an Atkinson cycle effect. An evolved mechanical kinetic energy recovery system which will deliver better round trip efficiencies with a design tailored to store a smaller quantity of energy over a reduced time frame with a non-driveline configuration has also been developed. Brake specific fuel consumption maps have been computed in this paper for a gasoline engine 2 litres, in-line four, turbocharged and directly fuel injected which gives significant fuel savings during light and medium loads operation.(Boretti and Scalzo, 2013). Optimization for maximum output from total cycle of engine pistons by constraining its acceleration, variations in injection patterns and start of ignition timings have resulted in improvement in fuel economy of the engine. (Xia et al., 2012; Hiroyasu et al., 2003) Advancements have taken place in the field of optimization of journal bearing and crankpin design for minimum stresses and durability. Different materials and manufacturing processes have also been suggested (Ghorbanian et al., 2011; Summer et al., 2015; Choi et al., 2009; Ho et al., 2009; Montazersadgh and Fatemi, 2007). This literature review clearly indicates the lack of research in the area of crankshaft oriented fuel economy improvement. No literature concerning the design modification of crankweb to improve fuel economy of the engine is available. This research void has been thoroughly addressed in this paper.

This research paper suggests a novel design of engine crankshaft which is a spinoff from the current crankshaft designs which will allow the driver to take his/her vehicle to higher speeds without actually accelerating the engine to higher R.P.M by converting the extra or unnecessary torque obtained from the Low RPM situation as compared to situation when the same engine is operated at a higher RPM into angular velocity of the crankshaft of the engine. Only this portion of extra torque will be converted to angular velocity of the crankshaft thereby the output angular velocity as well as the output torque of the modified crankshaft system in the Low RPM situation will be equal to that provided in the High RPM situation. Hence, improve the fuel economy of the vehicle because of the fact that engines run more efficiently on lean air-fuel mixtures when operated at low RPM (In comparison to when they are operated at a higher RPM). In order to accommodate the wear and tear of the crankshaft due to the gearing action, design parameters like crankpin diameter, journal bearing diameter, crankpin fillet radii and journal bearing fillet radii have been optimized for output parameters like *maximum stress which will be the major area of concern due to the additional loads experienced due to meshing of the two shafts* has been calculated using finite element analysis with ANSYS Mechanical APDL and minimum volume (As it is of utmost importance to reduce the amount of material that is used in manufacturing of the crankshaft system to leave minimal footprint on the environment (Metsec, 2014).) using integrated Artificial Neural Network-Multi objective genetic algorithm(NSGA II). The data set for the optimization process has been generated using Latin Hypercube Sampling technique. Finite Element Analysis' have been done on a set of 60 data points which have been developed using Latin Hypercube Sampling using which an Artificial Neural Network was simulated using Bayesian Regularization as the activation function in the hidden and output layers. Validation of the network has been done using an additional five sets of five data points. Hence a set of optimum solutions have been suggested that will satisfy the specified criteria. Since only theoretical values have been calculated and experimental testing of the modified crankshaft system has not been done, further research is required to estimate the actual wear and tear and the resulting frictional losses of the gear tooth due to meshing. This idea if implemented will solve one of the most serious problems of mankind that is depleting fossil fuel reserves and global warming.

This paper has been divided into five major sections. The first section talks about the modifications which have been done in the suggested design of the crankshaft system. The second section describes the advantages that the proposed design has over existing techniques for improving the fuel economy of the vehicle. The third section describes the finite element analysis' performed on crankshafts having different dimensions of afore mentioned parameters. The last section explains the network formulation and optimization of the crankpin and journal bearing dimensions in accordance to the constraints defined. *This paper will also be the first to optimize a crankshaft system with two shafts thereby will serve as a model for subsequent research to be carried out in this area*.

2 Design Modifications

This section describes the design changes that have been done in the existing crankshaft design to serve the purpose of the idea.

2.1 Crankweb

The proposed system will be a twin shaft system comprising of the modified crankshaft and the final shaft whose output R.P.M will be higher than that of engine with torque reduction. Design of a counterweight has been merged with the design of a gear to enable the crankweb to serve the purpose of balancing the crankshaft as well as rotate the final shaft at an angular speed higher than its own speed as shown in Fig. 1.

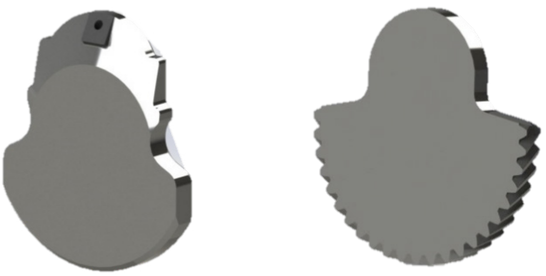

Fig. 1 (a) Design of the original Crankweb **(b)** Design of the Modified Crankweb

2.2 Crankshaft System

The modified crankshaft will not only convert the reciprocating motion of the piston-connecting rod assembly into the rotary motion but will also transfer the engine power to the final shaft instead of transferring it to the flywheel. It can be seen that in the proposed design (Fig. 3), the modified crankshaft rotates on bearings attached to its ends about its own axis while the final shaft will rotate on the bearing on one side and will be connected to the flywheel making only one set of crankwebs mesh with the final shaft at a time, that is, in the first 180^o of rotation crankwebs corresponding to the first and fourth crank throws will engage with the final shaft and in the next 180^o of revolution, crankwebs corresponding to second and third crank throws will be meshed.

Modified crankshaft and the final shaft will always be meshed together which has been ensured by making the geared region of the crankweb subtend angle greater than one eighty degrees at the centre of the crankweb which is clear from Fig. 3. So, by the time the first set of crankwebs will disengage with the final shaft, the second set of crankwebs will mesh with the same. The number of gear teeth on the crankweb was selected on the basis of the overdrive ratio that was supposed to be realised at the final shaft, module of the gear and the assumed diameter of the crankweb. This implies that the module of the final shaft will be same as that of the modified crankweb having lesser teeth as compared to the complete circular gear of the modified crankshaft. The diameter of the crankweb was taken in reference to the size of the crankweb of the original crankshaft to ensure that the size of the crankshaft remains same. Extensive experimental analysis has been done (Vaidyanathan, 2009) on the efficiency losses occurring due to meshing of helical gears. Experiments have been conducted for a set of four torque values. It has been clearly documented that for a helical gear having module of 2.14, pressure angle of 16.5 degrees and the number of teeth as 40, the efficiency is above 99.7%. This particular dataset has been selected from the experiments performed as the module, pressure angle and carrying torque values of the crankshaft are 2.25, 20 degrees and 160N-m respectively which are very close to the experimental values. Moreover, there would be a further improvement in the efficiency of each geared crankweb since each crankweb will not be meshed for the entire cycle with the final shaft as mentioned earlier.

The power that the engine is producing will be transmitted to the modified crankshaft which will in turn transmit the power to the final shaft. Routinely, the final shaft will transmit power to the flywheel and subsequently to the transmission system as shown in Fig. 3 unlike the original situation when the crankshaft is connected to the flywheel as shown in Fig. 2.

Fig. 4 gives a schematic about how the proposed system will work.

Fig. 2 Connection of Original crankshaft with Flywheel

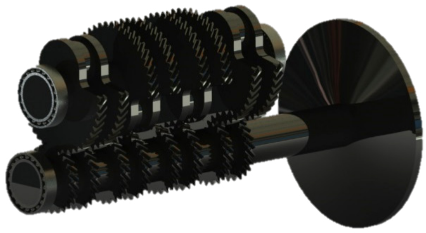

Fig. 3 Modified crankshaft system connected with Flywheel

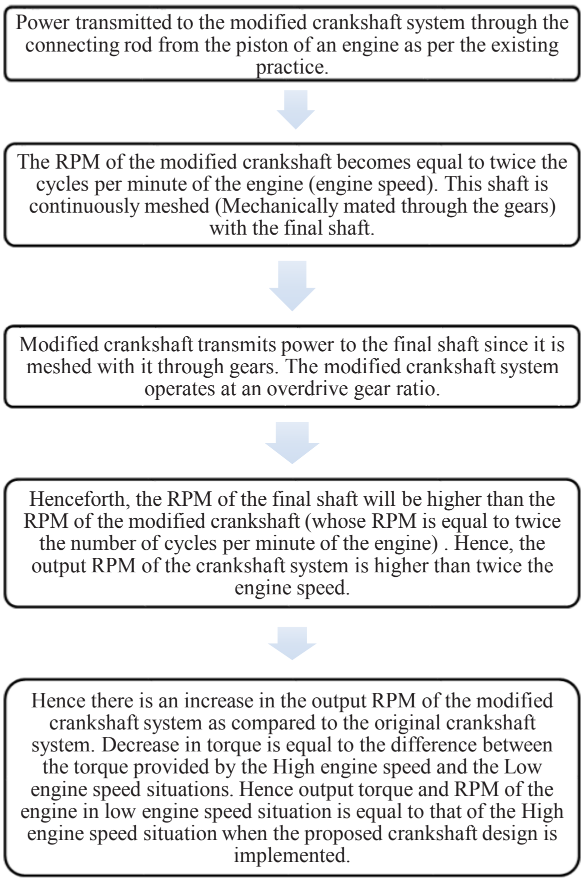

Fig. 4 Working Schematic of the Proposed Design.

2.3 Advantages of the New Design over Existing Solutions

Alternate Solution-1:- This system can be fabricated in the transmission system of the vehicle where we can use overdrive gear ratios between the driven and the driving gears hence achieves the same result. The concept of overdrive gear ratio is used in the transmission are generally the fifth or the seventh gears of the vehicles. Since, we frequently require to change the gears which are running at overdrive gear ratios, the type of gear used is epicyclic gear that will replace each pair of helical gears. This will result in an increase in weight more than the case when we just use a single shaft for maintaining the overdrive gear ratio, which is the proposed case. Consequently, the transverse loading on the shafts and the subsequent vibration increases. So, special attention has to be given to selection of shaft bearings, bearing housing and improvement in the rigidity of the gearbox making it very expensive and hence suitable for use in high end cars only. Another difficulty faced in adapting such a transmission system is that toe in will not be allowed which gives straight line stability for vehicles having rear wheel drive by reducing the turning tendency. Overdrive gear ratios are often controlled by computers and at times there may be glitches in the programming system where the computer may decrease the power of the engine when switches to overdrive ratio resulting in lower torque and inability to transverse slopes.

Alternate Solution-2:- The final drive ratio can be lowered to realise the same results. The propeller shaft transmits power to the drive shafts that rotate the rear wheels of the vehicle (considering rear wheel drive for explanation). There is an angular speed reduction and an increase in torque between the propeller shaft and the drive shaft which is controlled by the final drive ratio. The value of final drive ratio is roughly 4 (subject to the manufacturer and other design considerations) which means that the torque transmitted by the drive shaft will be approximately four times the torque transmitted by the propeller shaft. This torque is needed to accelerate the vehicle. The torque available at the tyres can't be reduced so if we reduce the final drive ratio then the torque available at the drive shaft will also be less which has to be accommodated by the increase in torque at the propeller shaft which implies thicker shaft, sophisticated universal joints to transfer higher torque and expensive differential housing. This will lead to an increase in weight which will be much higher than the proposed solution considering the dimensions of the propeller shaft. It also implies an increased cost of manufacturing of the joints and placement issues in case of sedans with low ground clearance.

Increase in weight will be less in the proposed design when only a single shaft for maintaining the overdrive gear ratio is used instead of installing planetary gear trains corresponding to each overdrive gear ratio. In case of the proposed model the rotation speed of the input shaft itself higher, the system is purely mechanical and modification of the transmission system is not required. This eliminates any hindrance to toe-in of the vehicle and the possibility of electronic glitches and failures. Also, the proposed design does not require any shifting of gears and the modified crankshaft will always be meshed with the final shaft, so it is not essential to design a very sophisticated bearing hence reducing its cost making it feasible to use in any vehicle.

These are the reasons so as to which, the proposed design is better than Alternate Solution-1. In comparison to the Alternate Solution-2, the overall weight of the proposed design will be less due to the addition of only one extra shaft in comparison to the increase in the dimensions of the entire propeller shaft.

3 Transient Structural Analysis

Fig. 5 depicts the approach that has been undertaken to solve the design and optimization problem.

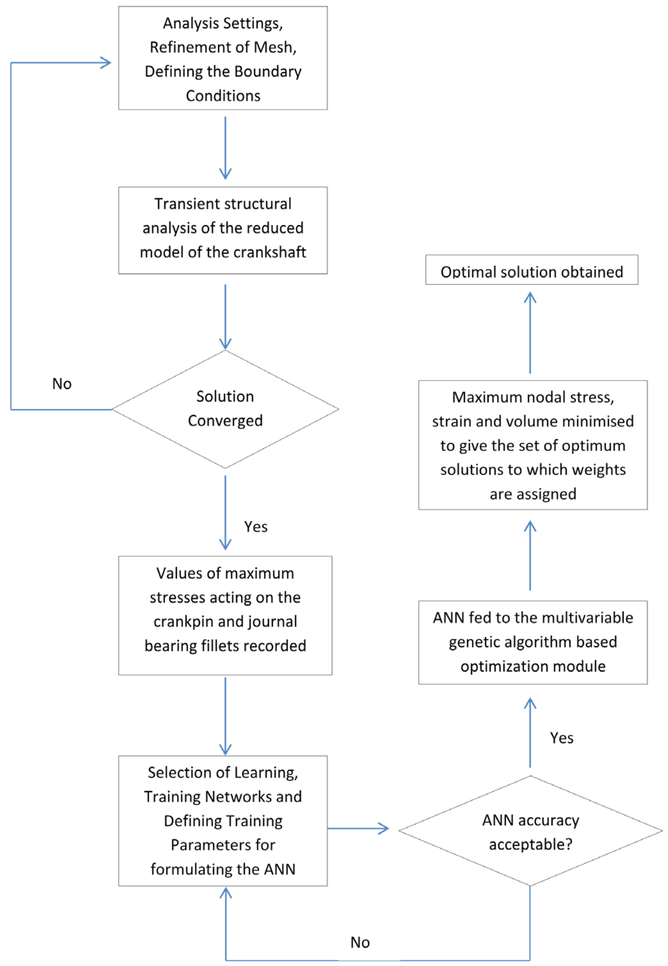

Fig. 5 Analysis and Optimization Schematic

3.1 Structural Analysis

To calculate the maximum value of stresses on the grar teeth, crank pin and the journal bearing fillets, forces acting on crankpin and gear teeth were calculated using the engine gas dynamics and inline engine balancing equations.

Material Selection-ASTM 182 F11 was selected as the crankshaft material. Forged crankshafts were used for analysis over cast crankshafts because of lower adhesive tendencies displayed by forged crankshafts that enable them to show better sliding tendencies with an aluminum bearing. The *Young Modulus* of ASTM 182 F11 2E+11, *Poisson's Ratio* is 0.29 and the *Mass Density* is 7900Kg/m3 In order to reduce the computational time required for performing the analysis, the crankshaft model taken into consideration for the analysis has been simplified using the symmetric design of the crankshaft with each of its crank throws having identical design. One crank throw model, one-half crank throw model and one-quarter crank throw model are a few of the models that could be used for the analysis. However, in order to ensure that the accuracy of the results isn't compromised, one crank throw model has been used because in one-quarter crank throw model which uses the least computational resources, there are chances of obtaining inflated stress values. Quasi static model has been used for fixing the boundary conditions of the crankshaft for the analysis which has enabled to further reduce the complexity of the model taken into consideration for the analysis. It has been assumed that the entire crankshaft is resting on non-linear supports which are the crankshaft journal bearings. Cylindrical supports were applied to the journal bearings of the crank throw which would constrain its radial and axial displacement but would allow tangential displacement of the nodes enabling the crankshaft to rotate about its axis. Forces were applied on the crankpin surface that would subtend an angle of 120^0 at its centre. Fig. 6. depicts the loads and boundary conditions applied on the crankshaft for the analysis.

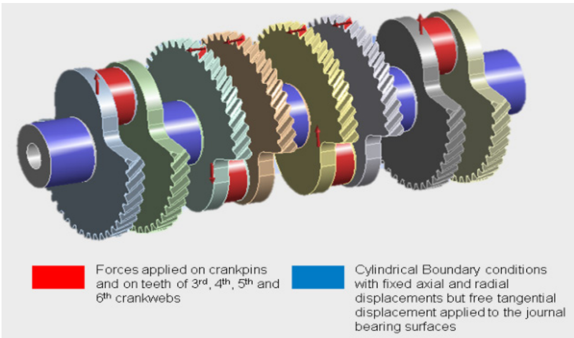

Fig. 6 Boundary conditions applied for analysis

Torsional analysis has been carried out on both the original crankshaft and the modified crankshaft after incorporating the additional loads acting on the crankweb.

It can be observed from the values of maximum stresses Figs. 7-8 that the torsional stresses generated are well below the yield limit which can be improved by modifying the fillet design.

Fig. 9 gives the meshing of the single crankthrow that has been considered for the finite element analysis in ANSYS.

Table 1 gives the transient analysis settings which have been used for solving the given problem for stress, which is the most important parameter to be considered while designing a crankshaft and its subsequent optimization. Coriolis effects were neglected while conducting the analyses

The values of the parameters have been set in such a way that there is an optimum compromise between the accuracy of the analysis and the computational requirement for the solution.

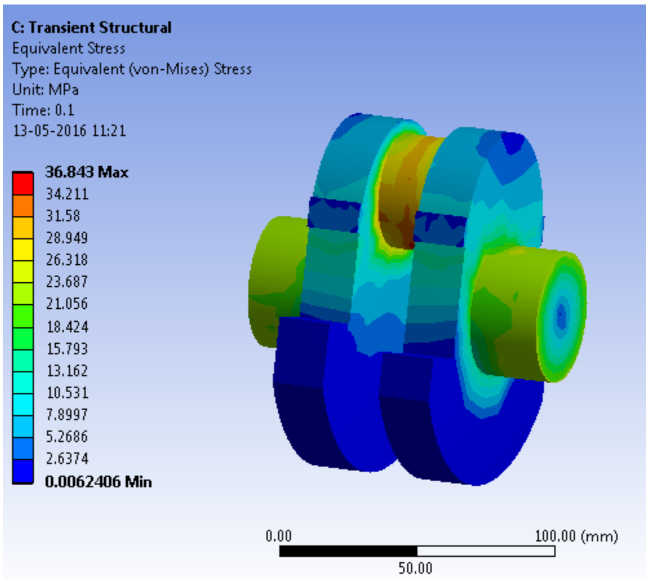

Fig. 7 Equivalent Torsional Stress-Original Crankshaft

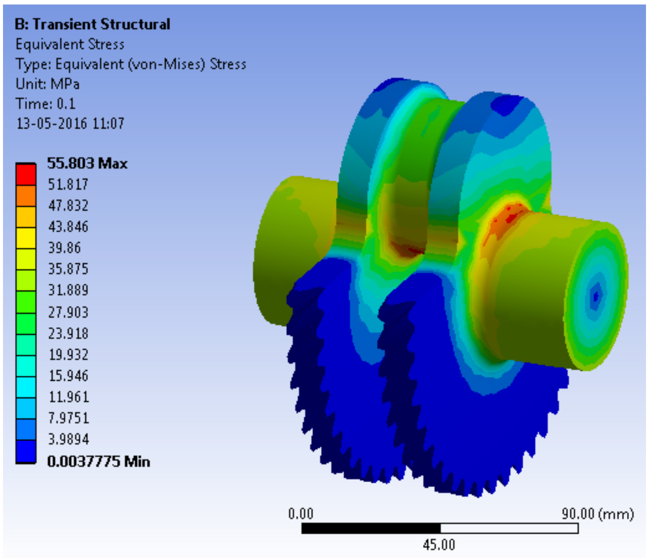

Fig. 8 Equivalent Torsional Stress-Modified Crankshaft

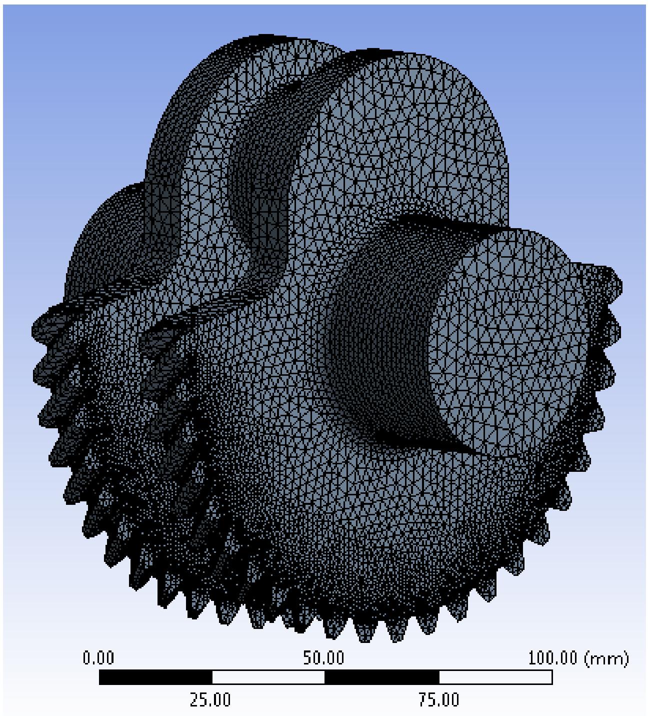

Fig. 9 Meshed Crankthrow Model

Table 1 Details of ANSYS Analysis Settings

SNo.	Name of Parameter	Value
1	Pre Stress Value	None
2	Number of Steps	1
3	Step End Time	0.1s
4	Auto Time Stepping	On
5	Initial Time Step	0.003s
6	Minimum Time Step	0.0005s
7	Maximum Time Step	0.05s
8	Time Integration	On
9	Solver Type	Iterative
10	Weak Springs	On

3.2 Sample Space generation for Analysis

The crankpin diameter, journal diameter, crankpin fillet radius and journal fillet radii for each crank throw were selected from the data of ten engines that were manufactured between the years 1999 and 2005 as depicted by Table 1. of Appendix-1. Limited data pertaining to the crankshaft dimensions were available and there was no data for engines that were manufactured in the recent years (last ten years or later). This data enabled us to set a range for the measurements considered for the analysis and subsequent optimization of the same. Since, we have no information about the underlying effects of factors on responses, it becomes imperative for us to use space filling designs. In our study, we use the Latin hypercube designs, which is one of the most popular space filling designs for deterministic computer simulation models. Latin Hypercube Sampling (LHS) is a stratified random procedure for efficient sampling of variables from their multivariate distributions. It was initially developed for efficiently selecting input variables for computer models for the purpose of Monte-Carlo simulations (McKay, 2000; Iman and Conover, 1980). It is efficient when used for structural analysis for estimating standard deviations and mean values. (Olsson et al., 2003). Latin Hypercube designs have become very popular among strategies for computer experiments. One advantage it offers is the creation of experimental designs with as many points as desired along with the space filling properties. It has been used by several researchers for sampling of design data points for crank shaft simulations (Chen et al., 2010; Mourelatos, 2005). Sixty data sets were extracted in the four dimensional workspace using the technique of Latin Hypercube Sampling in MATLAB.

4 Design Optimization

4.1 Selected Parameters

The parameters that were optimized for obtaining the datasets were the maximum stresses occurring on the crankpin and journal fillets which have to be minimised to reduce the possibility of fatigue failure; the stresses have been expressed in terms of the ANN generated functions and the volume function which is the sum total of the volume of the crankpin, journal bearings, crankpin fillets and the journal fillets of the crank throw considered for the analysis. The main objective of selecting the volume as a parameter was to minimise the weight and manufacturing cost of the forged steel crankshaft, which not only reduces the final production cost of the component, but also results in a lighter weight crankshaft which will increase the fuel economy of the engine. The volume can be given by the empirical formula show in Eq. (1).

$$\begin{aligned} Volume &= 3.14*0.25*X(1)*X(1)+3.14*0.5*X(2)*X(2)+ \\ &2*(X(3)*X(3)-3.14*0.25*0.25*X(3)*X(3))*3.14* \\ &X(1)+2*(X(4)*X(4)-3.14*0.25*X(4)*X(4)*3.14*X(2) \end{aligned} \tag{1}$$

X(1) = Crankpin Diameter
X(2) = Journal Bearing Diameter
X(3) = Crankpin Fillet Radius
X(4) = Journal Fillet Radius

4.2 Network formulation

Neural network has been successfully used by several researchers for predicting stress, torque, fuel consumption for crankshaft design (Hiroyasu et al., 2003; Ghorbanian et al., 2011). Feed forward network has been chosen which comprises of an input layer which takes the input parameters, a hidden layer that generates the relationship between the input and output parameters represented by synaptic weights and an output layer which predicts the outputs for the given input set using the generated relationship. The neural networks toolbox in MATLAB is used to formulate the artificial neural network. Several models were designed and tested to determine the optimal architecture, the most suitable activation function and the best training algorithm. The implementation of the network training has been done in batches whereby the entire training set is applied to the network before updating the weights. This training algorithm is faster and more accurate in comparison to incremental training where weights are altered after each dataset is fed to the network. Weights are assigned to each input which along with the bias are used to form the transfer function f. any differentiable transfer function may be used to generate the output. Mean square error is the default performance function that has been used for validation and testing of the generated network. Average squared error between the predicted and actual outputs can be expressed mathematically in Eq. (2)

$$F = mse = \frac{1}{N}\sum_{i=1}^{N}\left(p_i - a_i\right)^2 \tag{2}$$

The main parameters used for selecting ANN model were Regression Coefficient(R) values and Mean Absolute Percentage Error (MAPE) of the trained models which can be expressed by Eq. (3).

$$\text{MAPE} = \left|\frac{Actual - predicted}{Actual}\right| *100 \tag{3}$$

Four input parameters and two output parameters were taken into consideration for the development of the network. The dataset is shown in Table 2. Fifty-five sets of data were used for training and five sets of data were used for validation. Several networks were designed with trial and error procedure and tested with validation dataset. Bayesian Regularisation has been used for the activation function in the hidden layer as well as in the output layer. The learning algorithm used was GDM. Bayesian regularization has been selected as the training algorithm also because of its ability to produce better generalization capability as compared to early stopping as it uses all the available data instead of categorizing it into validation and training data set. The scatter plots enable to understand the problem of poor fits with some points. A network is considered to be acceptable if the R values are more than 0.9 (Demuth et al., 1992). Further, in order to select the number of neurons we made neural networks with neurons ranging from 2-20 and selected the model with least MAPE value.

Since, we were not able to get acceptable MAPE values for both Crankpin and Journal stress in the same network, so we developed 2 neural networks, one each having lower MAPE value for Crankpin stress and Journal stress respectively which can be referred from Figs. 10-11. Hidden layer consisting of 10 neurons is shown in Fig. 1. 3.28% for Maximum Crankpin stress and 5.76% for Maximum Journal stress. The regression coefficient (R) for validation data set was found to be 0.99, thereby, indicating a strong correlation between the experimental outputs and network outputs. The architecture for the networks developed is 4-7-2 and 4-10-2, for Crankpin stress and Journal stress respectively. The neural schematic of the developed networks are depicted in Fig. 13 and Fig. 15. Corresponding R *values are depicted* by Figs. 12 and 14.

4.3 Multi Objective Genetic Algorithm Optimization

The multi-objective Optimization Problem (MOP) can be defined as the problem of finding a vector of decision variables which satisfies constraints and optimizes a vector function whose elements represent the objective functions. These functions form a mathematical description of performance criteria which are usually in conflict with each other as in the case presented. Evolutionary multi objective optimization techniques

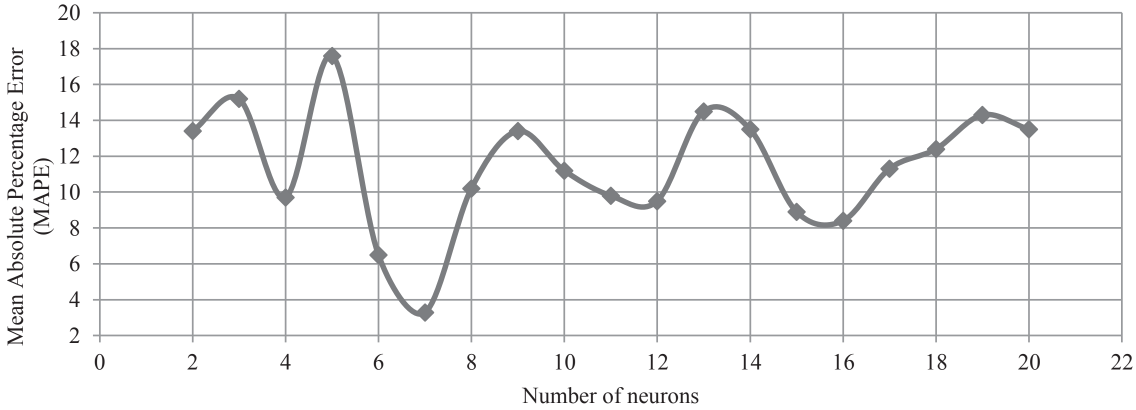

Fig. 10 Variation of mean absolute percentage error in prediction with number of neurons (for Crankpin stress)

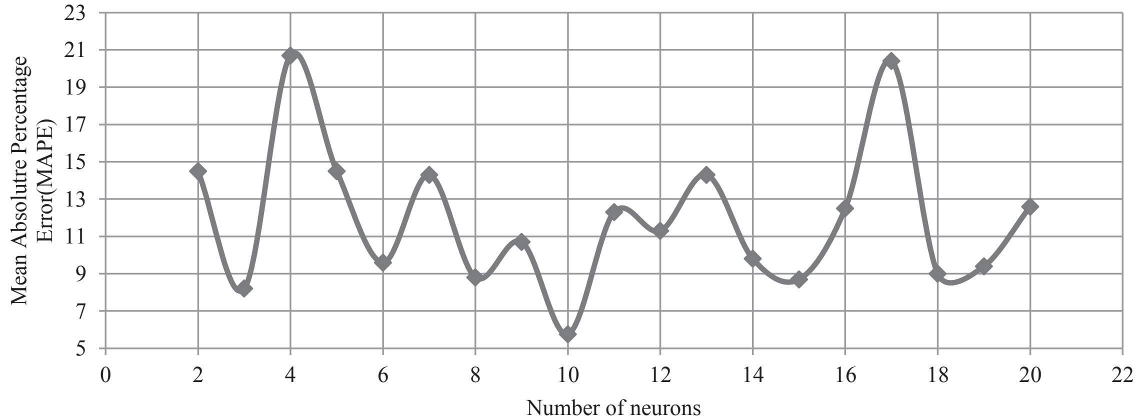

Fig. 11 Variation of mean absolute percentage error in prediction with number of neurons (for Journal stress)

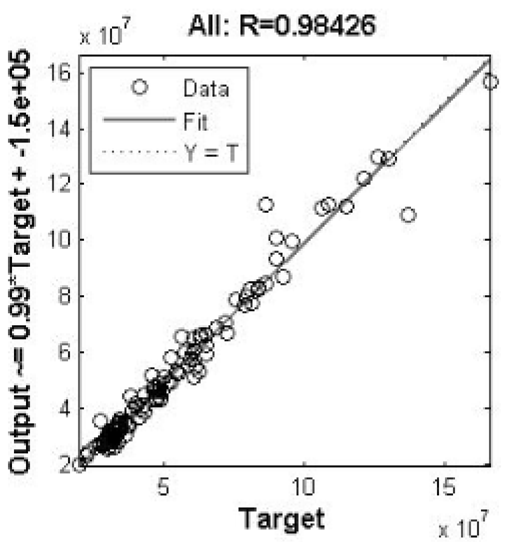

Fig. 12 Regression graphs for Neural network developed for Crankpin Stress (MATLAB)

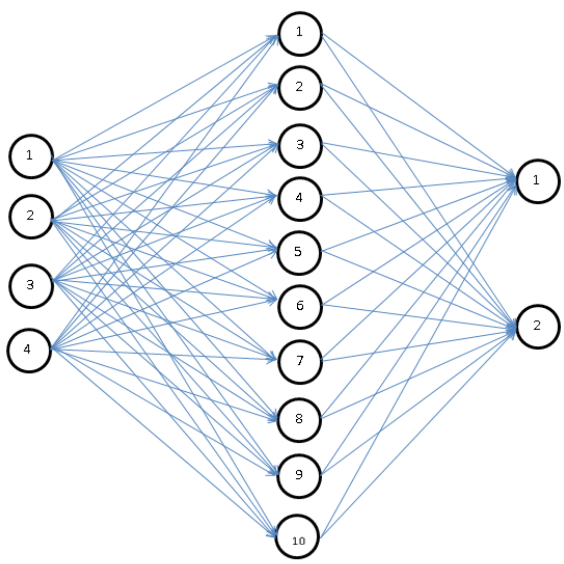

Fig. 13 Neural Network architecture (for Journal stress prediction)

including genetic algorithm and other Meta heuristic methods are powerful tools for optimization. Genetic algorithm has been successfully used by several researchers for the design optimization of critical components like crankshaft, cams, aerofoil (Obayashi et al., 2000). The Multi-Objective Genetic Algorithm model attempts to create a set of Pareto optima for a multi objective minimization. Pareto optimality is named after an Italian economist, Vilfredo Pareto (1906). A solution can be considered Pareto optimal if there is no other solution that performs at least as well on every criteria and strictly better on at least one criteria.

In genetic algorithms, a chromosome is a set of parameters which define a proposed solution to the problem it is trying

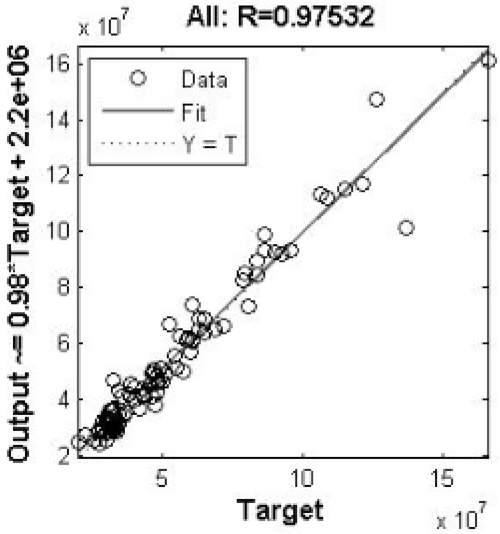

Fig. 14 Regression graphs for Neural network developed for Crankpin Stress (MATLAB)

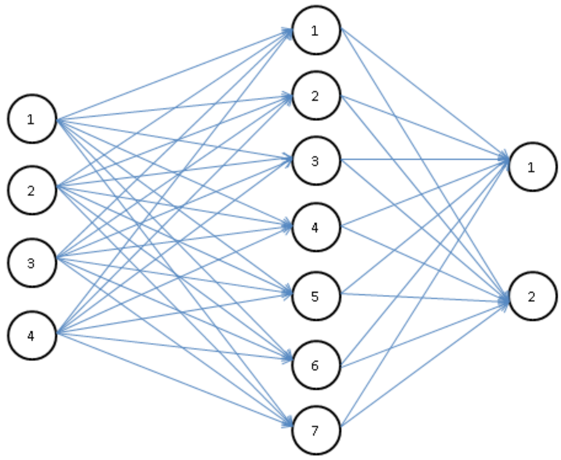

Fig. 15 Neural Network architecture (for Crankpin stress prediction)

Table 2 Comparison of engines with traditional original crankshaft and modified crankshaft systems

S.No	Parameters	Engine-A (traditional Crankshaft)	Engine-B (modified crankshaft system)
1	Tyre Diameter	600mm	600mm
2	Operating Power	44.742kW	44.742kW
3	Gear Ratio	1:1	1:1
4	Final Drive Ratio	3.937	3.937
5	Input RPM of engine	5376	3000
6	Final Output RPM at the crankshaft system	5376	5376
7	Output Torque of the crankshaft	79.51N-m	79.51N-m
8	Speed	154.35Km/h	154.35Km/h
9	Fuel Consumed one hour	16.39L of diesel	11.62Lof diesel
10	BSFC	310g/Kw-hr	220g/Kw-hr
11	Mileage	9.42Km/L	13.28Km/L

to solve (Konak et al., 2006). The genetic operators such as cross-over, mutation and selection make use of the fitness evaluation of the chromosomes. Selection operators are more likely to choose the fit parents for cross-over, while mutation is inclined towards the least fit individuals. In this study, we use an ANN model to formulate the Fitness function. This multi-objective optimization problem (MOP) in the present study is to minimize the three output parameters which are crankpin fillet stress, journal bearing fillet stress and volume. It is solved to obtain solutions by using controlled elitist genetic algorithm (a variant of NSGA-II) in optimization tool of MATLAB on an Intel® I5® 2.40 GHz with 8 GB of ram.

Following are the upper and lower bounds to the crankshaft measurements:

1. Crankpin Radius= 39.94-51.98mm
2. Journal bearing radius= 46-59.99mm
3. Crankpin filler radius=1.35-5.84mm
4. Journal bearing fillet radius=1.60-6.93mm

Parameters of the multi-objective genetic algorithm are: Population type: double vector, Population size: 50 (since No. of variables <5), Creation function: Constraint dependent, Selection: tournament selection with tournament size = 2, Crossover fraction = 0.8, mutation fraction = 0.2, Mutation: Constraint dependent, Crossover: intermediate with crossover ratio of 1.0, Migration direction: forward with fraction of 0.2 and interval of 20, Distance measure function: distance crowding, Pareto front population fraction = 0.35 and Termination criteria: 100* No. of variables=100*4=400.

5 Discussion

Table 2 (Appendix) gives the sample comprising of 60 sets of data that have been used for the analysis and subsequent optimization. The table also gives the values of the maximum stresses that act on the crankpin and journal bearing fillets calculated using finite element analysis. The selected overdrive gear ratio is 1.72 which implies that the final angular speed and the effective torque realized at the final shaft will be 1.792 times 0.558 times respectively as that of the modified crankshaft. Higher speed can be achieved at lower engine RPM using the proposed crankshaft system instead of the original crankshaft. The following Fig. 16 is the engine map of Saturn 1.9L DOHC engine which has been selected for the comparison of the original and the modified crankshaft. For comparison of the crankshaft designs, operating conditions of the two engines have been kept the same

It can be concluded from Table 2 (Data extracted from Fig. 16) that by installing the modified crankshaft system, higher speed can be achieved at lower engine RPM which will save fuel. Since the operating power of the engine is same for both the cases that have been considered, the output torque will remain the same which will ensure same acceleration and capability to

Table 3 Pareto Set of Optimized Results

S.No.	Crankpin Diameter (mm)	Journal Diameter (mm)	Crankpin Fillet Radius (mm)	Journal Fillet Radius (mm)	CrankPin Stress (Pa)*10^3	Journal Stress (Pa)*10^3	Volume (mm^3)
1	39.94	46.00	1.35	1.60	34700	94500	141463.06
2	51.79	59.98	5.81	3.32	29100	89600	250522.93
3	39.94	46.00	1.35	2.01	34700	90600	141806.465
4	40.03	58.65	2.01	6.93	32500	54100	226348.553
5	51.51	46.96	5.58	1.72	31000	107000	172353.811
6	40.48	46.40	2.58	2.56	34200	86900	146106.24
7	49.22	47.31	5.42	1.72	31300	105000	169343.978
8	46.23	47.23	4.55	3.60	32000	85600	163908.18
9	47.77	51.76	4.28	4.93	31400	71400	193217.431
10	44.54	49.41	5.33	4.12	31100	77700	175181.149
11	50.89	59.88	5.58	5.46	29600	67700	253155.158
12	51.73	59.97	5.68	6.78	29800	60100	260519.342
13	45.23	51.23	2.20	4.10	33300	74200	180860.43
14	43.19	46.65	4.49	3.80	32300	79800	156155.348
15	46.75	51.18	5.53	4.56	30600	75300	190177.36
16	40.25	58.52	2.03	5.27	32600	58900	219809.131
17	43.62	48.39	5.15	3.67	31500	81400	166958.95
18	40.16	58.90	2.08	6.68	32500	54600	227194.05

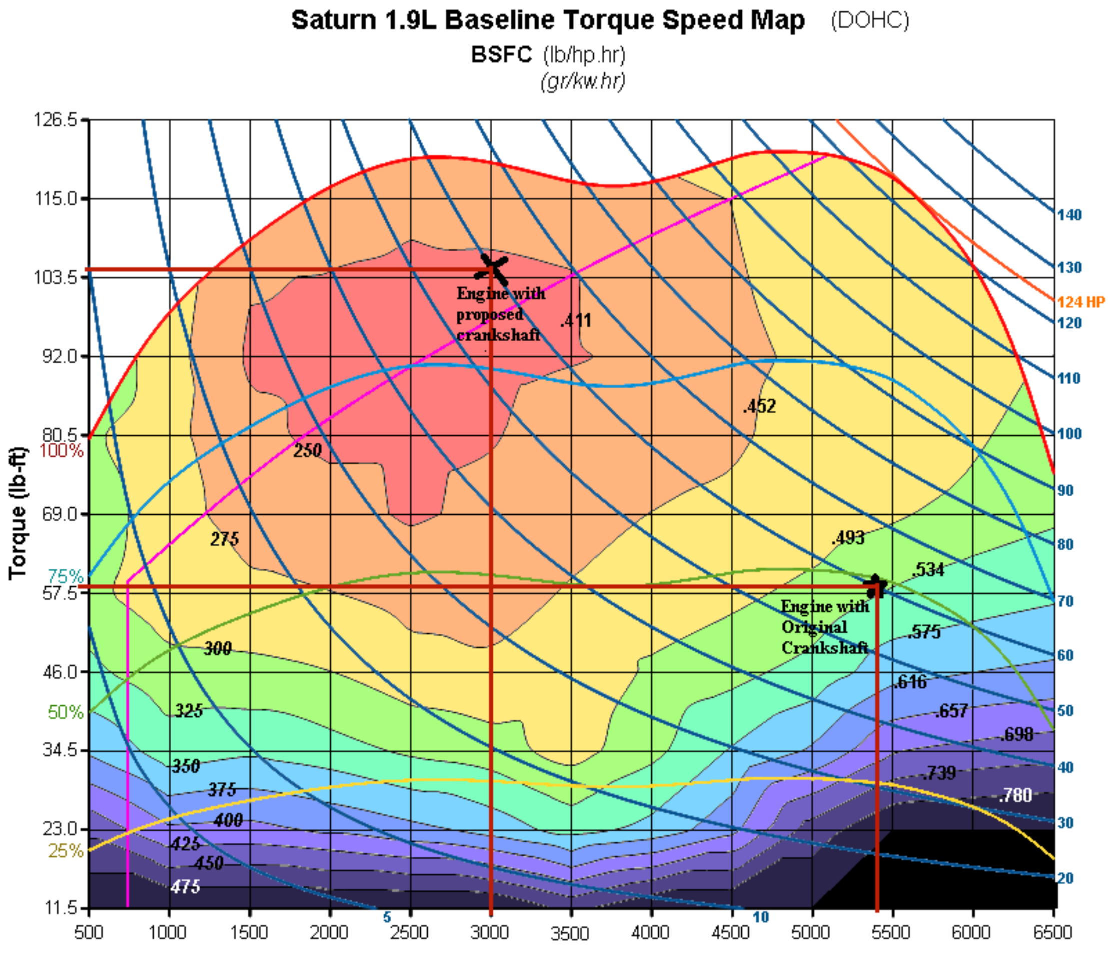

Fig. 16 Torque-bsfc map for Saturn DOHC Baseline-1.9L Engine (www.ecomodder.com)

traverse slopes. It can be seen that the fuel economy of the vehicle if driven on an engine with the modified crankshaft system installed will increase by 3.86Km/L in the case considered. So in a way the modified crankshaft system enables to combine the potential benefits of revving the engine at high and low R.P.M. Table 3 gives the sets of data that were obtained after performing multi-objective genetic algorithm optimization. Since, we have a multi-objective optimization problem, the optimum solutions form a "Pareto Front". The solutions correspond to the non-dominated individuals which present the best solution for all the three objective functions simultaneously. Further, since we have three objective functions, the "Pareto front" is a surface in three dimensional spaces. The designer can choose the appropriate design parameter combination from the Pareto front by assigning suitable weights to the objectives as per the requirement of the overall vehicle design Table 3. Pareto Front obtained from Multi-Objective Genetic Algorithm Optimization in MATLAB It can be observed from Table 3 that the stresses acting on the crankpin fillet lie around 31MPa irrespective of any change in the dimensions of the crankpin diameter and fillet radius thereby indicating a possibility to exploit these dimensions for obtaining minimum volume and minimum surface area with which the connecting rod will be rubbing during the combustion cycles. It can be deduced that solution sets 4, 12 and 18 will give the minimum value of stresses however the volume will be higher. It can be can be observed that mere increase in the values of crankshaft dimensions does not give significantly improved results as compared to when the increase of value of one parameter is in relation to the other parameter. Results 5 and 11 show that when the journal diameter is constant, increase in journal fillet radius results in a significant reduction in the maximum stress acting on the journal fillet. However, results 10 and 13 indicate that the effect is not as steep in the case when the journal fillet radii are almost equal and there is a significant increase in the value of journal diameter clearly pointing towards another area of exploitation for reduction in the material used.

6 Conclusion

The design suggested in this paper will allow the driver to take his/her vehicle to higher speeds without actually accelerating the engine to higher R.P.M. hence managing to save fuel. Moreover, the increased weight due to the additional shaft has been accommodated to the maximum possible extent by optimizing the design parameters of the crankshaft to obtain minimum stresses on the crankpin and journal fillets in order to avert the possibility of fatigue failure which is largely dependent on the maximum stress values apart from the number of cycles that can't be altered to a major extent. Hence a set of optimum solutions have been suggested that will satisfy all the criteria. It can be concluded from the optimization analysis that in order to obtain the minimum values of maximum stresses acting on the journal fillet, the journal fillet radius must be increased while keeping the journal diameter to a lower value. However, the values of the crankpin fillet radii and diameters do not have a significant impact on the stress values. Hence depending on the prioritization of the designer, one of the optimal designs can be selected for minimum stress and volume of the material used. of Since experimental analysis of the modified crankshaft system has not been done, further research is required to estimate the actual wear and tear and the resulting frictional losses of the gear tooth due to meshing. This idea if implemented will solve one of the most serious problems of mankind that is depleting fossil fuel reserves and global warming.

References

Al-Baghdadi, M. A. R. S., Al-Janabi, H. A. K. S. (2000). Improvement of performance and reduction of pollutant emission of a four stroke spark ignition engine fueled with hydrogen–gasoline fuel mixture. *Energy Conversion and Management*. 41(1), pp. 77-91. https://doi.org/10.1016/S0196-8904(99)00080-1

Agarwal, A. K. (2007). Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. *Progress in energy and combustion science*. 33(3), pp. 233-271. https://doi.org/10.1016/j.pecs.2006.08.003

Akansu, S. O., Dulger, Z., Kahraman, N., Veziroğlu, T. N. (2004). Internal combustion engines fueled by natural gas—hydrogen mixtures. *International Journal of Hydrogen Energy*. 29(14), pp. 1527-1539. https://doi.org/10.1016/j.ijhydene.2004.01.018

Boretti, A. (2012). Towards 40% efficiency with BMEP exceeding 30bar in directly injected, turbocharged, spark ignition ethanol engines. *Energy Conversion and Management*. 57, pp. 154-166. https://doi.org/10.1016/j.enconman.2011.12.011

Boretti, A., Scalzo, J. (2013). Novel crankshaft mechanism and regenerative braking system to improve the fuel economy of passenger cars. In: *Proceedings of the FISITA 2012 World Automotive Congress*. (pp. 19-44). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-33841-0_2

Chen, X., Yu, X., Ji, B. (2010), Study of crankshaft strength based on iSIGHT platform and DOE methods. In: 2010 International Conference on Measuring Technology and Mechatronics Automation. 3, pp. 548-551. IEEE. https://doi.org/10.1109/ICMTMA.2010.290

Choi, K. S., Pan, J. (2009). Simulations of stress distributions in crankshaft sections under fillet rolling and bending fatigue tests. *International Journal of Fatigue*. 31(3), pp. 544-557. https://doi.org/10.1016/j.ijfatigue.2008.03.035

Demirbas, A. (2007). Importance of biodiesel as transportation fuel. *Energy policy*. 35(9), pp.4661-4670. https://doi.org/10.1016/j.enpol.2007.04.003

Demuth, H., Beale, M. , Hagan, M. (1992). Neural network toolbox™ 6. User Guide, COPYRIGHT, 2008.

Erkaya, S., Su, Ş., Uzmay, I. (2007). Dynamic analysis of a slider–crank mechanism with eccentric connector and planetary gears. *Mechanism and machine theory*. 42(4), pp. 393-408. https://doi.org/10.1016/j.mechmachtheory.2006.04.011

Fontana, G., Galloni, E. (2009). Variable valve timing for fuel economy improvement in a small spark-ignition engine. *Applied Energy*. 86(1), pp. 96-105. https://doi.org/10.1016/j.apenergy.2008.04.009

Fox, I. E. (2005). Numerical evaluation of the potential for fuel economy improvement due to boundary friction reduction within heavy-duty diesel engines. *Tribology International*. 38(3), pp.265-275. https://doi.org/10.1016/j.triboint.2004.08.010

Ghorbanian, J., Ahmadi, M., Soltani, R. (2011). Design predictive tool and optimization of journal bearing using neural network model and multi-objective genetic algorithm. *Scientia Iranica*. 18(5), pp. 1095-1105. https://doi.org/10.1016/j.scient.2011.08.007

Hiroyasu, H., Miao, H., Hiroyasu, T., Miki, M., Kamiura, J., Watanabe, S. (2003). Genetic algorithms optimization of diesel engine emissions and fuel efficiency with air swirl, EGR, injection timing and multiple injections (No. 2003-01-1853). SAE Technical Paper.

Ho, S., Lee, Y. L., Kang, H. T., Wang, C. J. (2009). Optimization of a crankshaft rolling process for durability. *International Journal of Fatigue*. 31(5), pp. 799-808. https://doi.org/10.1016/j.ijfatigue.2008.11.011

Huang, K. D., Tzeng, S.C. (2004). A new parallel-type hybrid electric-vehicle. *Applied Energy*. 79(1), pp. 51-64. https://doi.org/10.1016/j.apenergy.2003.12.001

Huang, K. D., Tzeng, S. C., Chang, W. C. (2005). Energy-saving hybrid vehicle using a pneumatic-power system. *Applied Energy*. 81(1), pp. 1-18. https://doi.org/10.1016/j.apenergy.2004.06.005

Iman, R. L., Conover, W. J. (1980). Small sample sensitivity analysis techniques for computer models. with an application to risk assessment. *Communications in Statistics – Theory and Methods*. 9(17), pp. 1749-1842. https://doi.org/10.1080/03610928008827996

Katrašnik, T. (2007). Hybridization of powertrain and downsizing of IC engine–A way to reduce fuel consumption and pollutant emissions–Part 1. *Energy Conversion and Management*. 48(5), pp. 1411-1423. https://doi.org/10.1016/j.enconman.2006.12.004

Konak, A., Coit, D. W., Smith, A. E. (2006). Multi-objective optimization using genetic algorithms: A tutorial. *Reliability Engineering, System Safety*. 91(9), pp. 992-1007. https://doi.org/10.1016/j.ress.2005.11.018

Lapuerta, M., Armas, O., Rodriguez-Fernandez, J. (2008). Effect of biodiesel fuels on diesel engine emissions. *Progress in Energy and Combustion Science*. 34(2), pp. 198-223. https://doi.org/10.1016/j.pecs.2007.07.001

Ma, F. , Wang, Y. (2008). Study on the extension of lean operation limit through hydrogen enrichment in a natural gas spark-ignition engine. *International Journal of Hydrogen Energy*, 33(4), pp.1416-1424. https://doi.org/10.1016/j.ijhydene.2007.12.040

Ma, F., Wang, Y., Liu, H., Li, Y., Wang, J., Zhao, S. (2007). Experimental study on thermal efficiency and emission characteristics of a lean burn hydrogen enriched natural gas engine. *International Journal of Hydrogen Energy*, 32(18), pp.5067-5075. https://doi.org/10.1016/j.ijhydene.2007.07.048

Ma, F., Wang, Y., Liu, H., Li, Y., Wang, J. , Ding, S. (2008). Effects of hydrogen addition on cycle-by-cycle variations in a lean burn natural gas spark-ignition engine. *International Journal of Hydrogen Energy*. 33(2), pp.823-831. https://doi.org/10.1016/j.ijhydene.2007.10.043

Manzie, C., Watson, H., Halgamuge, S. (2007). Fuel economy improvements for urban driving: Hybrid vs. intelligent vehicles. *Transportation Research Part C: Emerging Technologies*. 15(1), pp. 1-16. https://doi.org/10.1016/j.trc.2006.11.003

McKay, M. D., Beckman, R. J., Conover, W. J. (2000). A comparison of three methods for selecting values of input variables in the analysis of output from a computer code. *Technometrics*. 42(1), pp. 55-61. https://doi.org/10.1080/00401706.1979.10489755

Metsec by voestapline, (2014). Environmental impacts of steel. URL: http://www.metsec.com/sustainability/environmental-impacts-of-steel/

Molina, S., Guardiola, C., Martín, J., García-Sarmiento, D. (2014). Development of a control-oriented model to optimise fuel consumption and NO X emissions in a DI Diesel engine. *Applied Energy*. 119, pp. 405-416. https://doi.org/10.1016/j.apenergy.2014.01.021

Montazersadgh, F. H., Fatemi, A. (2007). Stress analysis and optimization of crankshafts subject to dynamic loading. Final Project Report Submitted to the Forging Industry Educational Research Foundation and American Iron and Steel Institute, The University of Toledo, pp. 10-45.

Mourelatos, Z. P. (2005). Design of crankshaft main bearings under uncertainty. In: ANSA&mETA international congress. Athos Kassndra, Halkidiki, Greece.

Obayashi, S., Tsukahara, T., Nakamura, T. (2000). Multiobjective genetic algorithm applied to aerodynamic design of cascade airfoils. *IEEE Transactions on Industrial Electronics*. 47(1), pp. 211-216. https://doi.org/10.1109/41.824144

Olesky, L. M., Martz, J. B., Lavoie, G. A., Vavra, J., Assanis, D. N., Babajimopoulos, A. (2013). The effects of spark timing, unburned gas temperature, and negative valve overlap on the rates of stoichiometric spark assisted compression ignition combustion. *Applied Energy*. 105, pp. 407-417. https://doi.org/10.1016/j.apenergy.2013.01.038

Olsson, A., Sandberg, G., Dahlblom, O. (2003). On Latin hypercube sampling for structural reliability analysis. *Structural Safety*. 25(1), pp. 47-68. https://doi.org/10.1016/S0167-4730(02)00039-5

Rakopoulos, C. D., Dimaratos, A. M., Giakoumis, E. G., Rakopoulos, D. C. (2009). Evaluation of the effect of engine, load and turbocharger parameters on transient emissions of diesel engine. *Energy Conversion and Management*. 50(9), pp. 2381-2393. https://doi.org/10.1016/j.enconman.2009.05.022

Saerens, B., Vandersteen, J., Persoons, T., Swevers, J., Diehl, M., Van den Bulck, E. (2009). Minimization of the fuel consumption of a gasoline engine using dynamic optimization. *Applied Energy*. 86(9), pp. 1582-1588. https://doi.org/10.1016/j.apenergy.2008.12.022

Summer, F., Grün, F., Schiffer, J., Gódor, I., Papadimitriou, I. (2015). Tribological study of crankshaft bearing systems: Comparison of forged steel and cast iron counterparts under start–stop operation. *Wear*. 338-339, pp. 232-241. https://doi.org/10.1016/j.wear.2015.06.022

Tavakolpour, A. R., Zomorodian, A., Golneshan, A. A. (2008). Simulation, construction and testing of a two-cylinder solar Stirling engine powered by a flat-plate solar collector without regenerator. *Renewable Energy*. 33(1), pp. 77-87. https://doi.org/10.1016/j.renene.2007.03.004

Taylor, C. M. (1998). Automobile engine tribology—design considerations for efficiency and durability. *Wear*. 221(1), pp. 1-8. https://doi.org/10.1016/S0043-1648(98)00253-1

Vaidyanathan, A. (2009). An experimental investigation of helical gear efficiency. PhD Thesis, The Ohio State University.

Vetter, J., Barbezat, G., Crummenauer, J., Avissar, J. (2005). Surface treatment selections for automotive applications. *Surface and Coatings Technology*. 200(5), pp. 1962-1968. https://doi.org/10.1016/j.surfcoat.2005.08.011

Xia, S., Chen, L. , Sun, F. (2012). Engine performance improved by controlling piston motion: Linear phenomenological law system Diesel cycle. *International Journal of Thermal Sciences*. 51, pp. 163-174. https://doi.org/10.1016/j.ijthermalsci.2011.08.005

Yang, H., Wang, Z., Shuai, S., Wang, J., Xu, H , Wang, B. (2015). Temporally and spatially distributed combustion in low-octane gasoline multiple premixed compression ignition mode. *Applied Energy*. 150, pp.150-160. https://doi.org/10.1016/j.apenergy.2015.04.003

Appendix

Table 1 Existing Engine data used for selecting range of parameters considered for optimization

Model Name	Years Functional	Crankpin Diameter(mm)	Journal Diameter(mm)	Minimum Pin Fillet Radius(mm)	Maximum Pin Fillet Radius(mm)	Minimum Journal Fillet Radius(mm)	Maximum Journal Fillet Radius(mm)
Accent 1.6L	2001-2004	45	50	1.35	5.85	1.5	6.5
Elantra 2L	2004-2005	45	57	1.35	5.85	1.71	7.41
Tiburon 2L	1999-2005	45	57	1.35	5.85	1.71	7.41
Sonata 2.4L	1999-2005	44.98	56.952	1.3494	5.8474	1.70856	7.40376
Kia Rio 1.6L	2003-2005	39.94	49.938	1.1982	5.1922	1.49814	6.49194
Kia Sephia 1.8L	1999-2004	44.94	54.938	1.3482	5.8422	1.64814	7.14194
Kia Optima 2.4L	2001-2005	44.98	56.982	1.3494	5.8474	1.70946	7.40766
Mazda Miata 1.8L	1997-2004	44.94	49.939	1.3482	5.8422	1.49817	6.49207
Mazda 3&6 2.3L	2003-2005	49.98	51.98	1.4994	6.4974	1.5594	6.7574
Mazda 3 2L	2004-2005	46.98	51.98	1.4094	6.1074	1.5594	6.7574
Mitsubishi Lancer 2L	2002-2005	47	49.999	1.41	6.11	1.49997	6.49987
Mitsubishi Galant 2.4L	2005-2006	45	57	1.35	5.85	1.71	7.41
Nissan Sentra 1.8L	2000-2004	39.956	49.94	1.19868	5.19428	1.4982	6.4922
Nissan Altima 2.5L	2002-2004	49.955	54.953	1.49865	6.49415	1.64859	7.14389
Subaru Impreza WRX 2L	2002-2005	51.983	59.992	1.55949	6.75779	1.79976	7.79896
Toyota echo 1.5L	2001-2005	39.992	46	1.19976	5.19896	1.38	5.98
GM AVEO 1.6L	2004-2005	43	55	1.29	5.59	1.65	7.15
Honda Civic 1.3L	2004-2005	39.976	49.976	1.19928	5.19688	1.49928	6.49688

Table 2 Simulation results for Latin Hypercube Sampled dataset

S.NO	Crankpin Diameter (mm)	Journal Diameter (mm)	Crankpin Fillet (mm)	Journal Diameter (mm)	Max Stress (Pa)*10^5	
					Crank pin	Journal
1	50.48	56.14	2.06	4.93	331	548
2	48.27	50.08	5.65	2.98	276	790
3	41.65	52.65	1.68	5.82	306	470
4	50.08	57.08	4.16	2.18	288	1150
5	46.06	58.01	5.35	5.73	340	715
6	41.04	59.88	4.90	2.00	256	1060
7	44.05	54.28	1.61	3.60	339	602
8	45.06	46.82	3.78	5.46	310	463
9	50.68	47.05	3.56	6.00	324	481
10	51.28	50.78	4.08	1.64	304	1660
11	41.85	57.31	4.45	6.71	297	464
12	51.08	49.15	5.80	5.91	367	584
13	51.88	57.78	2.43	4.49	284	522
14	44.26	49.38	3.11	4.13	324	606
15	50.88	59.18	2.36	4.31	273	804
16	41.45	51.71	1.98	3.24	357	786
17	43.25	48.45	5.43	4.66	306	459
18	49.47	49.61	4.68	4.75	301	648
19	49.07	54.98	4.98	6.26	308	383
20	51.68	52.41	2.58	6.09	332	497

21	46.46	51.01	5.58	5.55	318	595
22	40.24	58.24	4.38	3.78	195	397
23	49.88	54.51	3.71	6.18	296	398
24	50.28	53.58	4.23	4.84	313	480
25	47.47	59.41	3.48	3.51	299	630
26	48.07	49.85	2.13	6.80	328	467
27	48.67	55.68	3.41	6.44	275	510
28	45.46	56.61	2.21	5.02	287	495
29	46.86	51.48	2.81	5.29	331	457
30	42.25	54.05	3.18	5.11	317	591
31	47.07	47.28	3.33	2.35	332	965
32	40.44	46.35	1.46	3.15	323	800
33	42.65	53.11	5.50	4.40	297	884
34	40.04	57.54	5.20	2.62	297	835
35	41.24	58.94	4.75	6.35	308	381
36	48.47	47.98	3.63	2.27	330	1090
37	47.27	55.21	2.51	2.53	428	922
38	42.85	52.88	5.05	1.91	313	1210
39	49.67	46.12	3.03	2.71	224	838
40	40.64	51.25	1.91	4.04	315	612
41	43.65	48.22	4.83	3.42	319	809
42	44.66	56.84	4.01	6.62	286	625
43	47.87	50.55	2.73	3.95	294	757
44	48.87	53.35	3.26	2.09	301	901
45	42.05	47.75	2.28	6.53	320	604
46	45.66	54.75	2.66	6.89	348	523
47	43.45	50.31	5.73	4.22	374	726
48	45.86	56.38	5.13	1.73	229	1300
49	47.67	55.91	3.86	2.80	410	651
50	49.27	55.44	1.53	3.69	477	601
51	43.05	52.18	2.88	5.20	475	649
52	46.26	47.52	2.96	2.89	335	1370
53	45.26	48.92	5.28	5.38	339	541
54	43.85	58.48	1.76	5.64	333	489
55	40.84	48.68	1.39	2.44	429	861
56	46.66	58.71	1.83	1.82	428	957
57	51.48	53.81	4.31	3.07	298	1260
58	44.46	59.64	4.60	3.33	344	688
59	44.86	46.58	4.53	3.86	359	574
60	42.45	51.95	3.93	4.58	420	560