Uhandisi Journal Vol. 21 No. 2, September 1997, pp 22-34

AN ADVANCED COMPUTATIONAL APPROACH TO THE ASSESSMENT OF STRUCTURAL INTEGRITY OF PISTONS FOR INTERNAL COMBUSTION ENGINE

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ABSTRACT

Several researchers have reported different techniques aimed at enhancing the accuracy and efficiency of computational approaches to piston design analysis. However, whilst most of the analysis tasks are highly interactive, the reported techniques addressed only a subset of the required aspects, and hence could not fully achieve the set objectives. In the present paper, an advanced design analysis methodology for pistons is presented, whereby, tools for finite elements modelling, simulation of applied boundary conditions, and assessments of piston loading, attitude, and durability have been integrated. With this novel approach, less than 2% deviation between predicted and measured piston temperatures was observed, as compared with 5-20% when employed existing methods. Furthermore, the piston life subsequently predicted differed from accelerated test by only 4.8% which is also a significant achievement. The observed positive attributes are a result of increased computation efficiency which has been enhanced by more than 50%. However, further work is still required to improve the structures of individual computer codes and reduce the memory requirement of the coupled analysis tasks. This will obviously enhance the accuracy in the prediction of piston life further.

INTRODUCTION

The continuing demands towards increasing fuel economy, reductions in exhaust emissions and oil consumption with improved service life, have led to higher thermal and mechanical loading of diesel engine pistons. New design solutions are therefore required, and which can only be realised after critical assessments of piston durability and tribological behaviour of piston/cylinder assembly. The difficulties involved in conducting reliable measurement of piston loading on a running engine, for evaluation of durability have been adequately described by Mshoro and Mshana [1]. The current trend in the assessment of piston integrity is therefore to employ Computer Aided Engineering (CAE) approaches.

However, in order to take full advantage of CAE potential, the numerical methods should be capable of providing useful information relatively faster and at a lower cost than is the case with physical testing. Various researchers have therefore addressed different techniques aimed at enhancing the accuracy and efficiency of CAE approaches to piston design analysis. Morel et al. [2], reported an engine simulation code which permits integrated analyses of engine performance and component temperature distributions. The simulation has minimised errors due to manual data transfer and hence improved the efficiency and accuracy of temperature computation. However, since this procedure assumes that the Finite Elements (FE) mesh has already been generated, and does not include assessments of life and tribology, its contribution to the reduction in piston development time is minimal. In further studies by Reipert [3] and Miyakawa et al [4], routines for automated generation of FE mesh and application of boundary data were coupled to the procedure of piston life prediction. In relative terms, the efficiency of the design process was increased significantly. However, the assessment of piston integrity was not complete since analyses of piston attitude and tribology were not included in the overall computation. On the other hand, Hosokawa et. al [5], Goenka et. al [6], Keribar and Dursunkaya [7], Winship and Morgan [8], and Keribar et al. [9] efficiently analysed piston attitude and tribology but did not include fatigue life prediction.

In the present paper, a more advanced integrated methodology for the design analysis of diesel engine pistons will be presented. The methodology addresses most of the required aspects of design analysis to include those for simulation of engine performance and boundary conditions, prediction of piston temperature and strain, and assessment of piston durability, and evaluation of piston eccentricity (attitude) and corresponding reaction forces for quantification of oil consumption and slap noise, respectively.

INTEGRATION OF PISTON DESIGN OBJECTIVES

The integrity of a piston is normally judged by its durability, tribological performance, and slap noise within the cylinder. In order to evaluate the above mentioned performance characteristics correctly, accurate variations of strain and temperature with time over the piston have to be known. In the present work, the variations of piston temperature and strains were determined by FE analysis as detailed in the previous publications by the present author [1, 10 - 13]. Fig. 1 depicts the relevant process flow diagram. The computed temperature and strains were then used as input to the assessments of piston attitude, slap noise, oil consumption, and fatigue life.

In the predictions of piston attitude, ring friction, and oil consumption, the PTL-SLAP software package [14] was used, and which passed through three main stages. Firstly, the facility converted the displaced shape information into radial deflections. During the second stage, the program took the information on radial deflection together with the relevant engine mass and geometrical data and calculated the motion of the piston within the cylinder during the engine cycle. The piston motion was computed at discrete time intervals throughout the engine cycle by the integration of instantaneous lateral and rotational acceleration of a rigid piston. In doing so, the program assumed that the contact occurs on the thrust/non thrust axis only. The instantaneous piston movement relative to cylinder centre line, piston tilt, mode of contact between the piston and liner, the piston reactions and location, and impact energy loss were then computed as output and could be used to quantify slap noise. The data on piston attitude, and cylinder gas pressure during the engine cycle (which was obtained from engine performance simulation) were used to calculate the inter ring gas pressures and subsequently the ring friction and oil consumption during the last stage.

On the other hand, the assessment of piston durability was restricted to the prediction of fatigue failure due to combustion bowl lip cracking. The PTL - LIFE software [15] was used for this purpose whereby, the material data was based on nominally mean properties and hence the calculated fatigue life was also considered to be mean life.

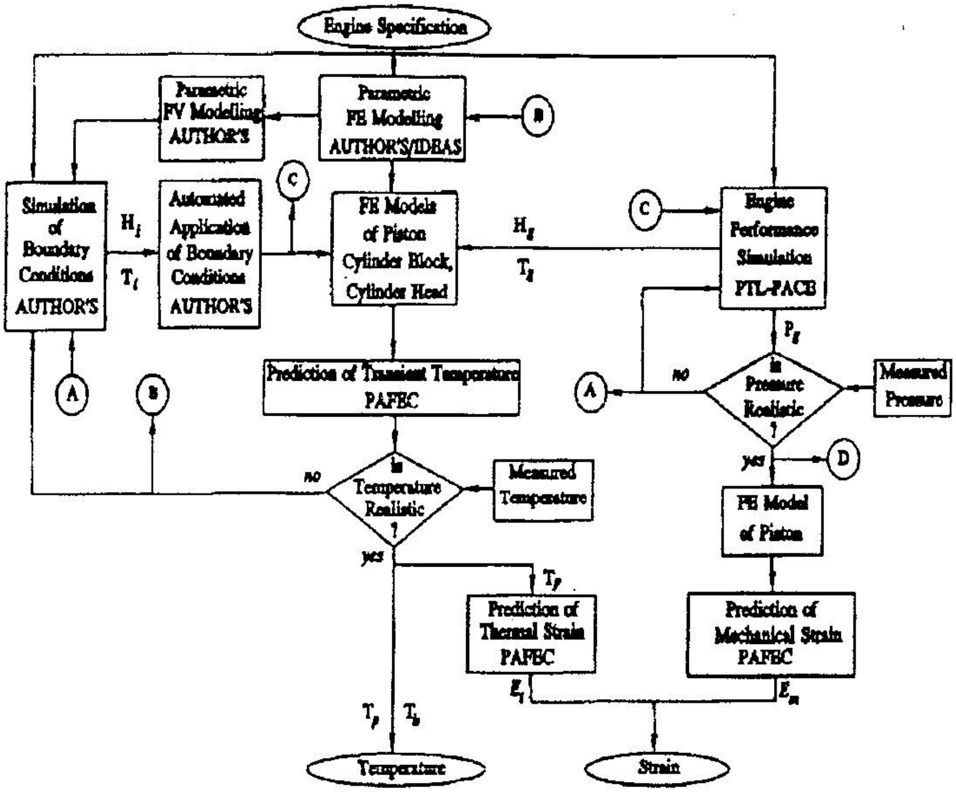

Figure 1: Process flow for computation of piston temperature and strain

The hoop stresses were considered to be the major components which could cause fracture of the combustion bowl lip. From the computed piston temperature and hoop strains, the program generated a strain-time-temperature history, and then calculated corresponding stresses using appropriate dynamic stress/strain curves included within the PTL-LIFE database. Having calculated the stresses, the computer code included the effects of creep on fatigue life which were incorporated through a mean stress factor. This was followed by the evaluation of the damage for each timestep from appropriate nomograph. The total damage for the repetitive cycle was then summed using a linear Miner 's law for cumulative damage. The detail of this procedure is reported elsewhere in the literature [13, 15].

Considering the expected large data volumes and the fact that most of the analysis tasks are highly interactive, the whole process of piston design evaluation had to be much more efficient than is currently the case. This was particularly necessary to minimise the processing demands of the repeat analyses. The interface computer programs in Fortran 77 language, and the relevant scripts for data management were therefore prepared in order to integrate different tools employed in the analysis, and minimise manual intervention in data preparation. The whole procedure is shown in Fig. 2, whereby temperature and strain were read directly from the routines shown in Fig. 1. By this action, more calculation iterations were performed until the required accuracy was attained. Furthermore, the numerical procedure could also be easily repeated with varied combinations of the initial design parameters, and hence more design alternatives were investigated.

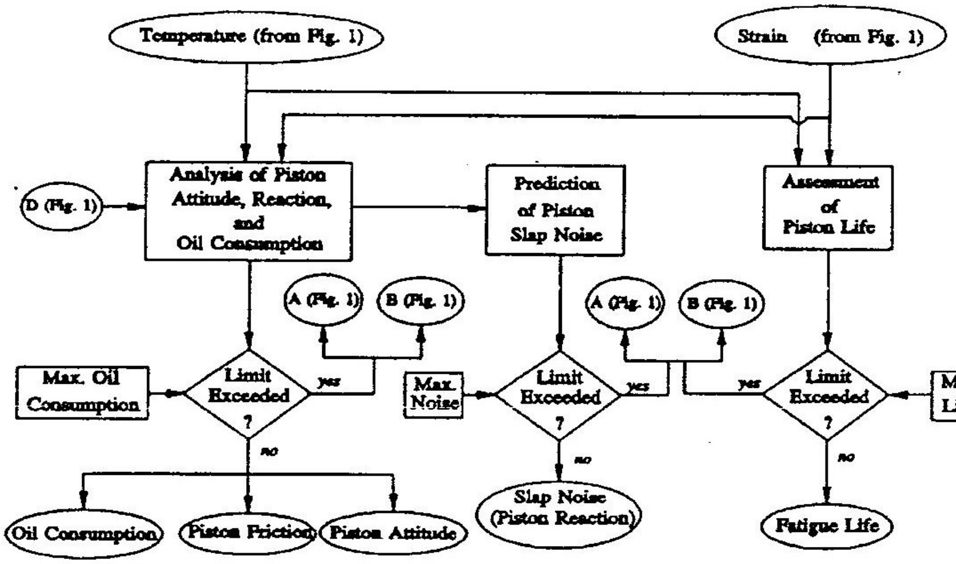

Figure 2: Integrated methodology for design analysis of pistons

EVALUATION OF THE INTEGRATED PISTON DESIGN METHODOLOGY

Piston fatigue Life

As a test case, the methodology was applied to compute transient temperature and strain over the piston and cylinder, piston attitude, corresponding reaction forces on the cylinder wall (which could be used to quantify slap noise), and piston fatigue life for an existing diesel engine, the Perkins Phaser 1000 Series operating under a gross thermal cycle. In order to simulate a gross thermal cycle, the engine load was abruptly reduced from rated conditions (156 *kW* at 2500 *rev/min*) to the low idle position at 650 *rev/min*. The idle position was maintained for 30 *seconds* and then accelerated back to 156 *kW* at 2500 *rev/min* where it was kept constant for another 30 *seconds* to complete one load cycle. Graphically, the thermal cycle is illustrated in Fig. 3.

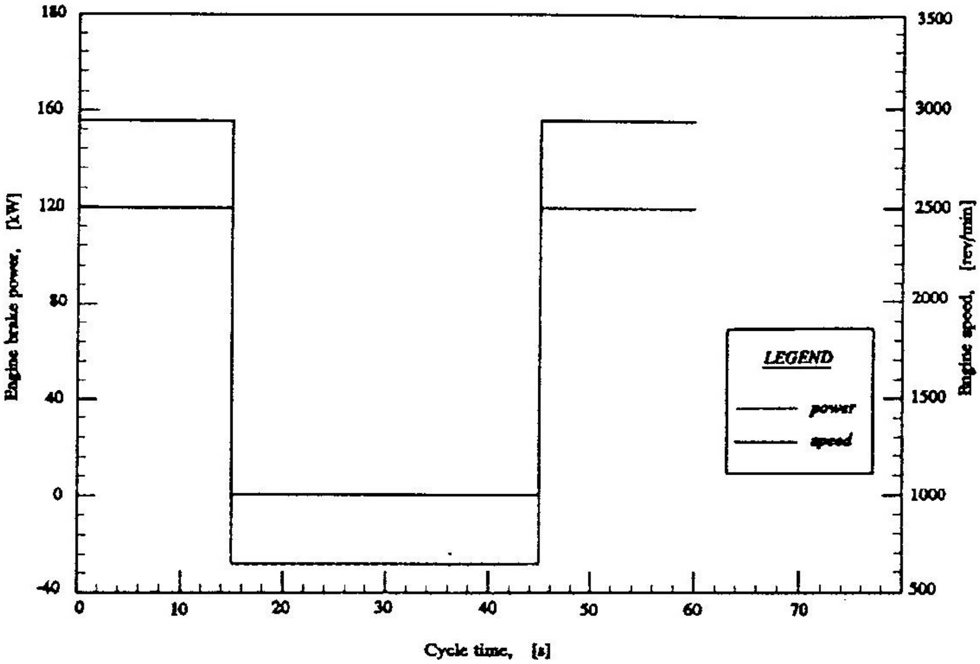

Figure 3: Gross thermal cycle

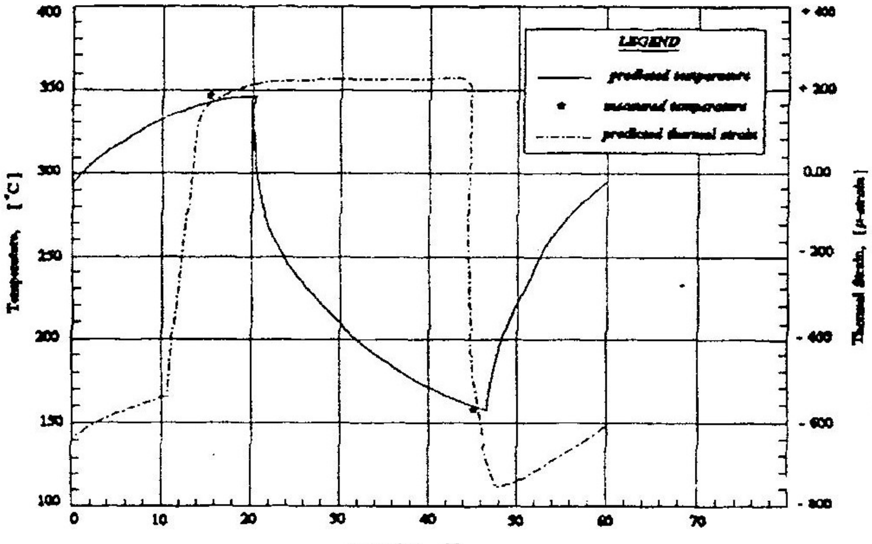

Figure 4: Maximum range of piston temperature and strain in one load cycle

By employing the procedure presented in Fig. 1, variations of piston temperature and strain were predicted over the piston operating under the selected engine load cycle. The maximum temperature on the piston during the cycle is presented in Fig. 4. Corresponding measured values depicted from another publication by the author [13] are also shown therein for comparison. It is observed that the piston will be subjected to a maximum temperature of 348 °C with a gradient of 200 °C/*cycle*. The corresponding transient strain is also shown in Fig. 4. Less than 2% deviation between predicted and measured temperatures was observed with the approach reported in the present work, as compared to 5-20% when employed existing methods. It was possible to realise the observed positive attribute since more calculation iterations could be performed until the required accuracy was attained. Furthermore, the numerical procedure could be easily repeated with varied combinations of the initial design parameters. In general, the computation efficiency was also enhanced significantly. Currently, it could take 25 *manweeks* to obtain accurate temperature results on a model with 3000 finite elements, whilst the same was obtained in 10-12 *manweeks* (4 *mandays* for a repeat analysis) with the integrated method. with the integrated method.

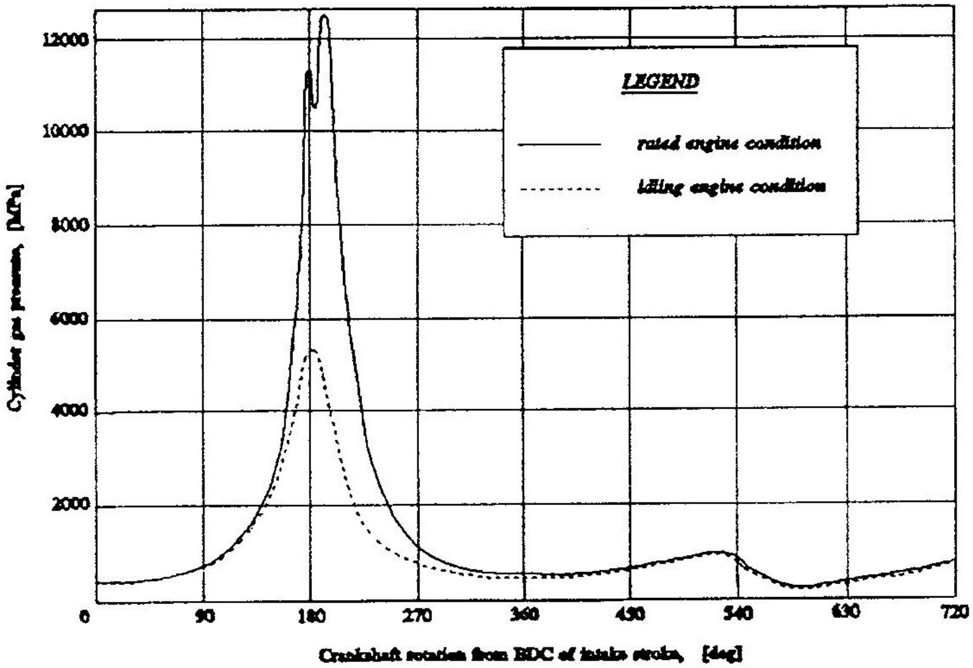

Figure 5: Predicted cylinder gas pressure at rated and idling engine conditions

In order to predict piston life, the thermal strain results obtained, were combined with the mechanical strain due to cylinder gas pressures. Measured data were used to derive the mechanical strain. The measurement details are reported elsewhere in the literature [16], where the maximum hoop stress $\{(\sigma_m)_{measured}\}$ in the bowl lip was +20.9 *MPa*. During the experiment, the piston was subjected to a maximum cylinder gas pressure $\{(P_g)_{measured}\}$ of 14.5 *MPa*. For the range of engine loads specified in Fig. 3, the engine performance simulation software, PTL-PACE, predicted maximum cylinder gas pressures $\{(P_g)_{predicted}\}$ of 12.4 *MPa* at 156 *kW*/2500 *rev/min*, and 5.5 *MPa* during idling at 650 *rev/min* as seen in Fig. 5. By interpolation,

the mechanical stresses at rated and idle engine operating conditions are obtained as +17.87 and +7.93 *MPa*, respectively. With the relevant Poisson effect and modulus of elasticity for the piston material, the corresponding hoop strains were computed as +218 and +97 *μ-strain*, respectively. Fig. 6 shows the resulted strain obtained after super positioning of the mechanical and thermal strains at the piston bowl lip.

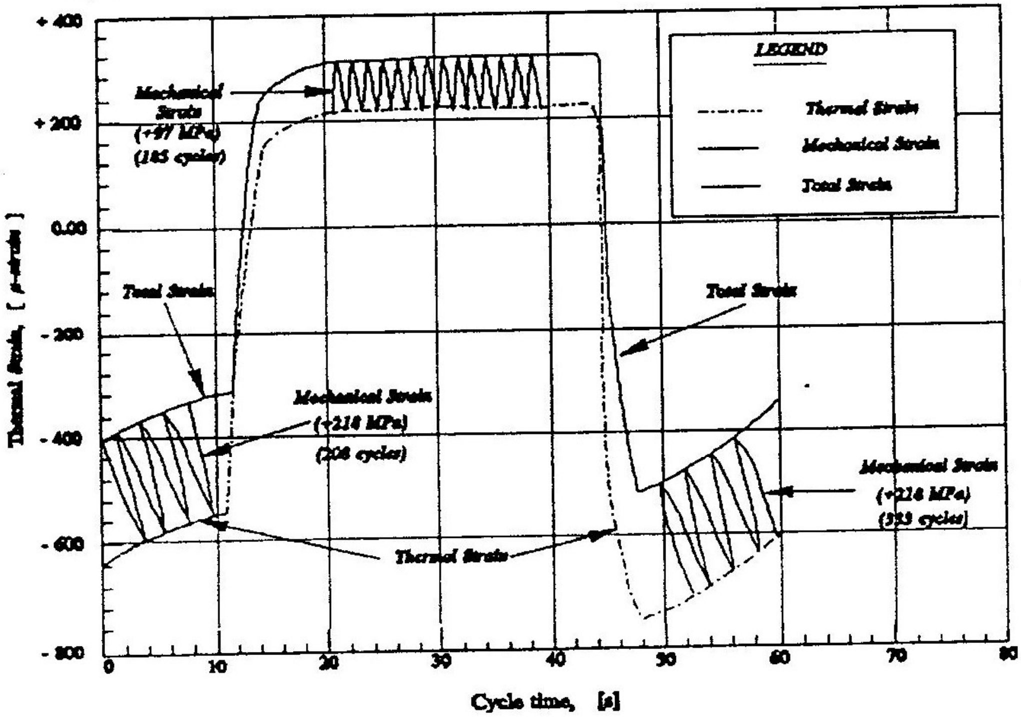

Figure 6: Super position of piston mechanical and thermal strains in one load cycle

The resulted strain curve was divided into three parts with the corresponding number of mechanical cycles per each part, n_m, obtained from the expression,

$$n_m = N_e.t_t.n_c \tag{2}$$

where,

N_e - engine speed
t_t - duration of respective parts of the thermal cycle
n_c - number of mechanical cycles in one load cycle

The temperature and total strain data given in Figs. 4 and 6, respectively were then input to the program for fatigue life assessment as illustrated in Fig. 2, and a piston life of 244292 hours was predicted. This value compares relatively well with data obtained through accelerated tests by Chan [13] who recorded a piston life of 232500 *hours*. The observed deviation of 4.8% between the predictive and measured results is within the acceptable limit. Further enhancement of accuracy can be achieved by more refinement of computational procedure than it is currently the case. Obviously, there may have been some inherent inaccuracy in the prediction of piston life by using a uniaxial fatigue software (PTL-LIFE) and other assumptions embodied in the computer program. For example, by the assumption that failure occurs at the fracture failure of a polished specimen is slightly optimistic when compared to crack initiation criteria, with a certain amount of crack propagation. Furthermore, the fatigue curves embodied in the computer database have been derived from strain controlled tests which is reasonable for thermally controlled cycles but is less so for mechanical cycles in which plastic strain is significant.

Piston Attitude and Reactions on the Cylinder

The predicted history of piston eccentricity in the cylinder bore is shown in Fig. 7. It is observed that whenever the piston is near the Bottom Dead Centre (BDC) - from 90° before BDC to 90° after BDC, the piston centreline at its top will be offset by up to 0.06 *mm* relative to the cylinder bore in the thrust side. On the other hand, the bottom of the piston will be in the non-thrust side and offset by up to 0.1 *mm*.

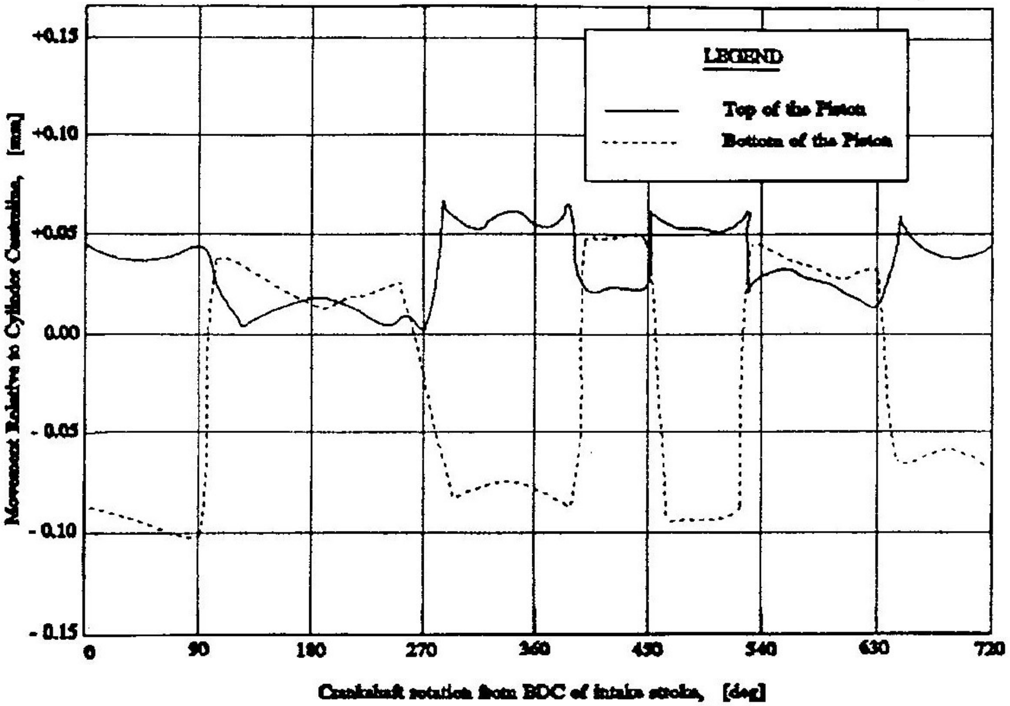

Figure 7: History of piston eccentricity (piston attitude) in the cylinder

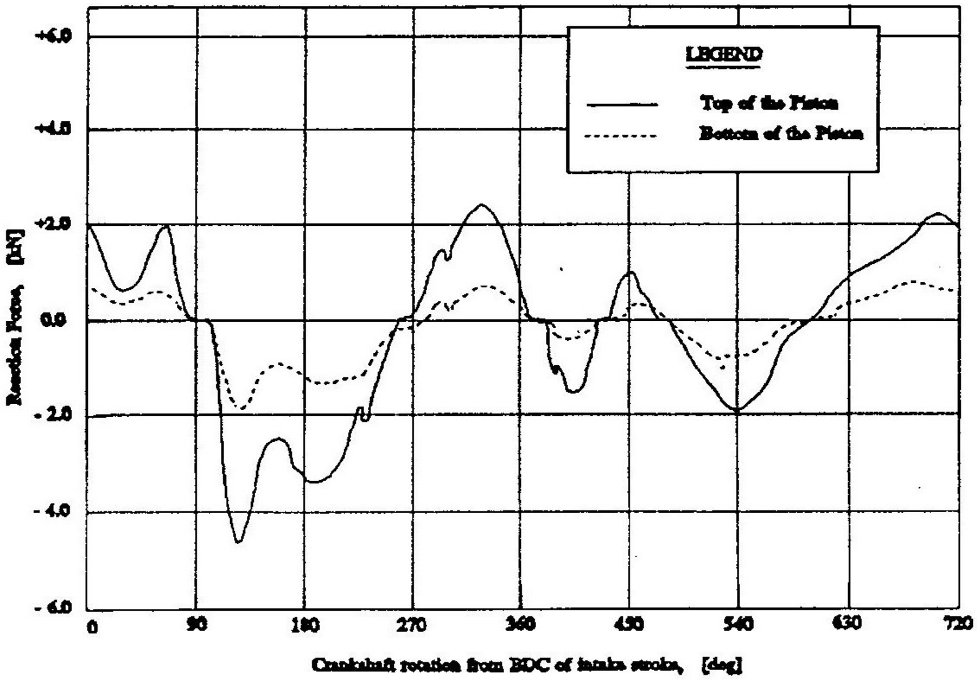

Figure 8: Piston Reaction Forces for Quantification of Slap Noise

The observed relative movement of piston with respect to cylinder will inevitably cause reactions on the cylinder which apart from being the major source of slap noise from the engine, could cause damage to the cylinder or/and piston. The corresponding instantaneous reaction forces are shown in Fig. 8.

CONCLUSIONS

A more advanced integrated methodology for the design analysis of diesel engine pistons has been presented. As a test case, the methodology was applied to compute piston temperature and strain, and corresponding life for the Perkins Phaser engine. The piston was observed to experience a maximum temperature of 348°C, with a gradient of 200°C/*cycle* to cause a strain gradient of +218 μ-*strain/cycle*. Subsequently, a piston life of 244292 *hours* was predicted. Apart from strength consideration, the history of piston eccentricity (attitude) within the cylinder was also checked whereby a piston tilt of up to 0.16 *mm* was observed to cause reactions on the cylinder walls of up to 4 *kN* which could be a major source of slap noise from the engine. The obtained results compared well with experimental data. Less than 2% deviation between predicted and measured temperatures were observed as compared to 5-20% when employing existing methods. Furthermore, the piston life predicted differed from accelerated test by only 4.8% which is a significant achievement. With the integrated approach to piston design, the overall computation efficiency has been improved remarkably. When compared to current methodologies, the computation efficiency has been enhanced by about 50% and 87% for the first and repeat analyses respectively. However, further work is still required to improve the structures of individual computer codes and reduce the memory requirement of the coupled analysis tasks. This will obviously enhance the accuracy in the prediction of piston life further.

ACKNOWLEDGEMENTS

This paper is based on the Ph.D research work by the author which was executed at the University of Dar es Salaam (UDSM) and Perkins Technology Limited (PTL), UK. The author therefore wishes to thank

UDSM authority for this great opportunity, the management at PTL for permission to conduct the work at its premises and publish the results, and the Swiss Development Corporation for sponsoring the study. The author is also indebted to Prof. J.S.Mshana, and Dr. P.Hanks for guidance, and all the researchers at PTL for constructive criticisms during the study.

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The manuscript was received on 20th February 1997 and accepted for publication, after corrections, on 29th October 1997