A proposed procedure for expressing the behavior of a full engine cycle by identifying its critical load timings

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Abstract. In the present study the authors propose a new algorithm for identifying the right loads that act upon a functional connecting rod during a full engine cycle. The loads are then divided into three categories depending on the results they produce, as static, semi-dynamic and dynamic ones. Because an engine cycle extends up to 720°, the authors aim to identify a method of substitution of values that produce the same effect as a previous value of a considered angle did. In other words, the proposed method aims to pin point the critical values that produce an effect different as the one seen before during a full engine cycle. Only those values will then be considered as valid loads that act upon the connecting rod inside FEA analyses. This technique has been applied to each of the three categories mentioned above and did produced different critical values for each one of them. The whole study relies on a theoretical mechanical project which was developed in order to identify the right values that correspond to each degree of the entire engine cycle of a Daewoo Tico automobile.

1. Introduction

Studies that highlight the behavior of connecting rods are being published periodically. They are fitted to a wide range of parts as it is considered that there are a few minor particularities that do not interfere with the generally accepted conclusions. The present study is structured as a case study as it is developed solely to a single type of an engine, the Daewoo Tico's one. In order to highlight the full behavior of a part under certain loads, one should consider the entire working cycle of that part under all known loads that act upon it. This is a tedious work in case of a connecting rod because of the sheer number of data that would have to be taken into account directly dependent on all 720° degrees of an engine cycle. Considering that previous studies showed that the behavior of the connecting rod are different depending on the type of loads considered to act upon them, this leads to a significant amount of work and data's to be processed [1].

The proposed method presents an algorithm which will identify only the values corresponding to engine cycle angles that produce a significant change when assessing the overall behavior characteristic to the functioning connecting rod inside the working engine; values that will override the ones that do not. Otherwise, all 720 values corresponding to an entire engine cycle would have to be taken into account each one as an individual load even though most of them will produce the same
results in terms of the connecting rod's behavior [2]. The values of the loads are only theoretical as they are extracted from a technical project of an engine design especially developed for this study. The resulted values were compared to similar ones considered by other researches in their studies and were found to be appropriate. The loads on the other hand were divided into three categories which have better highlighted the overall behavior of the considered connecting rod [3].

The method applies to all and has been adjusted accordingly. This shows that the principle of it may be used to a wide range of similar studies easing up consistently the logistics involved in such types of studies.

2. Method description

The loads are divided into three categories depending on the type of regimes that they are used in: static, semi-dynamic and dynamic. The division takes into account the analytical vector approach as loads are depicted as vectors which are applied to both ends of the connecting rod.

The distribution of loads produces different results as it acts upon the connecting rod's head and body. The two main loads which were considered in the present study are the tensile and the compressive ones. In case of the axial load their values are not at almost any point identical when applied either to the crank end or to the piston end of the connecting rod.

The tensile load extends to the entire upper section of the connecting rod's head spreading over 180° in an obvious opposition with the compressive load that only acts upon a 120° wide section (Fig. 1) [5].

2.1. Static load regime

In this case the load that acts upon the piston end of the connecting rod is being produced by the piston itself and the O-rings which are subjected to a full inertia load which drives the contact surfaces between the connecting rod and the bolts to be constrained. The loads that act upon the crank end of the connecting rod are divided into the tensile component of the axial load which tends to extend the part and the compressive one. These loads represent an effect of the tightening mounting method with the anti-friction bush and the bolts [2].

As stated above, this study uses the analytical vector approach (Fig. 2). Upon the body of the connecting rod (the piston end of it) we have both the tensile and the compressive components of the axial load that act each one at a time in a full engine cycle. The middle section of the connecting rod is being subjected to these loads as well as to bending in the swinging plane of the part and the plane perpendicular to it. These values were not considered as they are not making a significant change in the functional connecting rod's overall behavior compared to those that were taken into account for the part's crank end. This end named the connecting rod's head, is being also subjected to an axial load. Because the head of the part is widely filleted with the body, the compressive component is very much diminished in this case and thus only the tensile component is being taken into account.

The optimization procedure from the mass reduction point of view which has been carried out on the original 3D scan of the connecting rod showed that exactly this section may be improved with a larger fillet that will not only respect the original’s behavior under the same loads but will even enhance the stress distribution and thus its diminishment in that particular area. It also pointed out that although the optimization produces a loss of a few grams the stress and compression peaks and distribution do change for better when assessing the entire connecting rod’s behavior. That is considered a breakthrough by the authors of the research that makes subject of a different scientific paper [4].
The meanings of the symbols (Fig. 2) are as follows: $F_{tb}$ is the tensile component of the axial load that acts upon the connecting rod's body, $F_{cb}$ is the compressive component of the axial load that acts upon the connecting rod's body, $F_{th}$ is the tensile component of the axial load that acts upon the connecting rod's head, $F_p$ represents the pressure load produced by the bolts tightening, $\theta$ is the constrain angle and $\delta$ represents the movement under the imposed load.

2.2. Semi-dynamic load regime

In this case we will take into account that the load that acts upon the connecting rod is an inertia type of force which breaks down into two components: axial and normal. The axial component is also divided into the tensile and compressive type of forces. This type of load regime is different from the static one because it is considering the alternation of forces during an entire engine cycle and not at a given point in time as static regime did. Considering each individual value corresponding to every angle out of the 720 ones would be time consuming and very unproductive as we will demonstrate that certain critical values produce the same results. It is well known that the loads that act upon a certain point from within the connecting rod whole geometric surface have two major components: a bending and an axial form (Fig. 3) [2].

The bending load depends on the bending momentum and it is expressed as a function of the load normal to the part's weight center axis related to both angular and linear acceleration corresponding values. The variation of these loads during a half engine cycle from 0° to 360° is almost the same as the one from 360° to 720°. The $F_i$ symbol from figure 3 represents the inertia type of force distributed on the entire surface of the connecting rod.

As presented above, the values of the axial loads on each end of the connecting rod are not identical at any time due to different inertia loads. This makes it equal in terms of deciding which end of the connecting rod to choose since axial components distribution is the same at both ends. In the present study, the authors applied the load to the connecting rod's body or the piston end of it (Fig. 3). Results from the first half of an engine cycle had to be compared with the ones obtained from the other half. We have therefore overlapped the distributions under axial load characteristic to the first half of engine cycle with the one from the second half. Then we have divided these distributions into three different regions: "i", "ii" and "iii". Each segment of curve from each region received a letter from "a" to "f". By comparing those segments we have been able to choose the ones which showed different variations and eliminate the ones which were overlapping (Fig. 4).
The "i" region has two segments: "a" and "d". Both display different variations and do not overlap at any time.

The "ii" region has two segments: "b" and "e". The "b" segment shows a bigger variation in the compressive domain than "e" does up to 180° then both being almost identical which led to the conclusion that segment "e" may be eliminated from the process. The lowest value from the variation of segment "e" was considered and then compared with the lowest one from segment "b" in order to validate the decision.

The "iii" region has also two segments: "c" and "f". Since segment "c" displays a bigger variation in the tensile domain than segment "f" does the last one was eliminated. The lowest value from the variation.
variation of segment "f" was considered and then compared with the lowest one from segment "c" in order to validate the decision.

In order to highlight the behavior of the connecting rod on a full engine cycle our method states that it is enough to consider only the segments "a", "b", "c" and "d". Since the first change of sign is being recorded for the 76° angle the "d" segment will extend from 0° to 75°. In the same manner "e" will extend from 76° to 287° being divided around the 180° angle. The "f" segment will extend from 288° to 360°. Region "a" will extend from 361° to 435°. Region "b" segment will extend from 436° to 647° being divided around the 540° angle. In the end, region "c" will extend from 648° to 720°.

The critical values which will be considered in the evaluation process of the connecting rod on a full engine cycle are corresponding to the following angles: 0°, 76°, 361°, 410°, 495°, 578°, 646° and 720°. In addition to those, values that are corresponding to the 220° and 332° angles from segments "e" and "f" were also considered in order to validate the method. The resulted distribution is presented in figure 5.

2.3. Dynamic load regime

In this case we will consider the assembly which consists of the connecting rod, the piston and the crank (Fig. 6). The setup was developed in order to simulate as much as possible the real environment in which the process takes place. Thus it performs as it should under an inertia type of load. The difference from the semi-dynamic regime consists in the type of load that has been applied to the piston's head in order to generate the motion of the considered assembly. This load is considering also the normal component of the inertia type of force thus making it suitable for a full dynamic FEA simulation [3]. The inertia force or the total force as it is also known results from summing up the forces that appear due to the accumulated pressure of gases inside the cylinder, the translation inertia forces of moving masses, weight related forces and friction related forces. We will follow the same logic and apply the same working principle. The distribution under inertia load over the first half of the engine cycle has been overlapped with the one from the second half. Then we have divided these distributions into three different regions: "i", "ii" and "iii". Each segment of curve from each region received a letter from "a" to "f" naming particular areas (Fig. 7).

The "i" region has two segments: "a" and "d". Both display different variations and do not overlap at any time.

The "ii" region has two segments: "b" and "e". The "b" segment shows a bigger variation in the compressive domain than "e" does up to 180° then both being almost identical which led to the conclusion that segment "e" may be eliminated from the process. The lowest value from the variation of segment "e" was considered and then compared with the lowest one from segment "b" in order to validate the decision.

The "iii" region has also two segments: "c" and "f". Since segment "c" displays a bigger variation in the tensile domain than segment "f" does the last one was eliminated. The lowest value from the variation of segment "f" was considered and then compared with the lowest one from segment "e" in order to validate the decision.

In order to highlight the behavior of the assembly on a full engine cycle it is enough to consider only the segments "a", "b", "c" and "d". Since the first change of sign is being recorded for the 76° angle the "d" segment will extend from 0° to 75°. In the same manner "e" will extend from 76° to 287° being divided around the 180° angle. The "f" segment will extend from 288° to 360°. Region "a" will extend from 361° to 435°. The "b" segment will extend from 436° to 647° being divided around the 540° angle. In the end, "c" will extend from 648° to 720°.
The critical values which will be considered in the evaluation process of the connecting rod on a full engine cycle are corresponding to the following angles: 0°, 76°, 361°, 410°, 499°, 574°, 646° and 720°. In addition to those, values that are corresponding to the 215° and 333° angles from segments "e" and "f" were also considered in order to validate the method. The resulted distribution is presented in figure 8.

Fig. 7. Inertia load distribution from 0° to 360° overlapped with the one from 360° to 720°.

The critical values which will be considered in the evaluation process of the connecting rod on a full engine cycle are corresponding to the following angles: 0°, 76°, 361°, 410°, 499°, 574°, 646° and 720°. In addition to those, values that are corresponding to the 215° and 333° angles from segments "e" and "f" were also considered in order to validate the method. The resulted distribution is presented in figure 8.

Fig. 8. Inertia load distribution at given critical angles.
3. Conclusions

In the case of the static regime the loads are represented by the two sub-components of the axial load, namely: the compressive load and the tensile load. In case of the semi-dynamic regime the loads are represented by one of the two components of the inertia load, namely the axial load along a full engine cycle (this gives it the semi-dynamic character). In case of the dynamic regime the loads are represented by the inertia load. Those three regimes give us a complete perspective over the overall behavior of the connecting rod in a full engine cycle [6].

The proposed method applies to the regimes that stretch over an entire engine cycle. It aims to identify the values considered as critical that would simulate the behavior of the connecting rod just as if we would had to consider the all 720 of them that are corresponding to the angles from a full engine cycle.

In order to perform FEA analyses for all three regimes, constraints and loads should be set from the beginning. In the case of the two last regimes it would be a tedious work to perform FEA analyses for each value corresponding to the angles from a full engine cycle. Thus, the need for a method that would identify several values that would respect the overall distribution of the connecting rod under a load, arisen.

In the case of the semi-dynamic regime we have identified eight critical values that do respect the trend line imposed by all 720. In addition we have considered two more values from the dismissed curve segments in order to show that they do not interfere with the final result and the method's working principle. We can observe that values corresponding to the two additional angles are not affecting the trend line imposed by the other values as they are smaller.

In the case of the dynamic regime we have also identified eight critical values that do respect the trend line imposed by all 720. We have also considered two more values from the dismissed curve segments in order to show that they do not interfere with the final result. We can observe that values corresponding to the two additional angles are not affecting the trend line imposed by the other values as they are smaller.

The method proves that in the case of FEA analyses considering only 8 critical values out of 720 would provide the user with the same perspective over the connecting rod's behavior under given loads. The method may be extended to other types of working cycles as well not to mention all forms of connecting rods.

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