LOAD HISTORY AND STRUCTURE ANALYSIS OF UTILITY VEHICLES

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Abstract

Due to statistics 90% of the damages can be attributed to material fatigue in the scope of mechanical engineering.

We can reduce the risk of damage – among others – by adequate dimensioning methods. Which method is applied, the knowledge of the load history is absolutely indispensable. One of the possible analysis of the load history when we set different stress levels, and the numbers are counted, when the load history is crossing these preset values. These numbers are used for lifetime estimation.

The authors are suggesting a method for the determination of the expectable values of the stress level crossing numbers.

Keywords: load history, lifetime estimation, stress level crossing method.

1. Introduction

The fundamental principles of the dimensioning of machines, vehicles by the consideration of fatigue load have been set in the previous centuries. In spite of this the considerable advance of the 'technical sciences' especially in the field of material sciences, the technological processes, the analysis of the both sides i.e. qualitative, quantitative sides of the load history/spectrum gave new information for dimensioning, meanwhile the firm/wellknown basis of the fatigue process has been used at present days. The finite element method is an appropriate tool for the structure analysis.

Basically the designing process is the determination of the geometry for the load – either dynamic or static – by the consideration of material properties. This simple process has some complicated details when we investigate the load, the selection of materials/manufacturing, processes, not to mention to meet certain technical, economical requirements, optimum criteria.

The first phase of the design process is the forming of a general concept which meets the requirements of the product. This phase is a multilevel geometrical design consisting of preliminary nets of geometry, the necessary cross sections, and at the end of it the consideration of local effects.

On the other path there is the analysis of size effects, which is the adaptation of the mechanical properties measured on probes to the real geometry and shape.

The success of the design and of the product – acknowledged by the market – depends on the precise determination of base data resulted by thoroughful analysis and the concept adopted in the procedure.

As a consequence of the above mentioned, the design as a process is a synthesis of the result/achievement of different sciences with multidisciplinary overlapping, such way an adequate approximation with a definite goal.

Therefore if we analyse the dimensioning process on the whole, we can say that our product suits the requirements of strength under given circumstances – road, load, service conditions – and has a well defined service life, and meets the requirements of environment protection and economy and other expectations that have not been mentioned. It has a contradiction, because we can be convinced of the product reliability only after its use, service. This way at the beginning of the concept forming the information needed, could be gained, obtained from similar vehicles under similar service circumstances.

The final task – the end of the design – is to harmonise the two parts – influencing each other's condition – i.e. the vehicle and the traffic loads (among others: kinematics load from the road surfaces, dynamics of the vehicle determined by the traffic conditions, etc.) shortly to finish a competitive market-able product.

The vehicle and the road cannot be considered independent, because they influence each other that means the vehicle gets the impacts from the road, the vehicle modifies the road, road profile, road geometry, this way the technical parameters will be changed because of their interaction.

2. Models

First of all we have to verify the input data which determine the stress of our construction, and define them with the required accuracy.

Input data are the variables, which determine the stress state of the vehicles, considering that the stresses, the changing of stresses – in magnitude, phase, frequency – are the dominant factors influencing the service life of vehicles.

During the design process we use series of models in different directions with the same goal. One of the possible modelling procedures is, when we are examining the operation/running model and on the base of it we frame a load model, after a dimensioning model, further on modelling the structure itself, its geometry, elaborating a mechanical and computational model.

We are dealing now only with the operation, load and computational models.

Maybe the separate handling of the load and operation models is not practical in the case of road vehicles, advisable to consider it, because at a given load, load distribution, operational conditions determine the stress state at a given point. In other words the stresses caused by the operation conditions are superimposed to the stresses resulted by the loads/load distribution. Necessary to emphasise that the load, the load distribution are stochastic variables.

The loads on the vehicle structures are generally distributed loads, but there are areas where they are considered as concentrated loads, there are special cases when a simplified model requires concentrated load in spite of their distributed character. For the illustration of the change of pay load, load distribution, the fluctuation of passengers at stops can be mentioned.

Sometimes the separation of the load and operation model can be justified e.g. in case of better data handling, in such cases we integrate their effect at the determination of mechanical stresses.

We refer to the possible separation of the load, load distribution and operation, this way can be measured their effect simultaneously at given points of vehicles by strain, acceleration measurement. In this case it is obvious that between the excitation pay (load, road, surface, traffic conditions, etc.) and the measured stress there is a transfer function derived from the vehicle mechanical properties. In the preliminary design phase the separate handling of the pay load, operation model is the typical way, while the analysis of their simultaneous effects – including the excitation and transfer function – is used in the verification phase of design.

The weights of the above detailed variables, e.g. the mass of the fuel at the airplanes are changing significantly during operation.

The change in time of the pay load can be followed and can be registered (e.g. at buses the passenger counting).

The own weight of the vehicle and the pay load are determining the initial values of the load/stress function, this initial value is changing in time, and of course the function itself too, the function depends on the operation conditions.

Take the manoeuvres of the vehicles determined by the traffic conditions as an example – accelerating, braking, turning –, or the road conditions. The forces generated by them are of three dimensional, generally with a dominant direction.

It is well-known – among others – that there is a relation between the masses (the quantity of the own and pay) and the operation conditions. An example could be: a given road quality – it can be characterised by unevenness, 'roughness' – effects the travel speed, increasing the load decreasing the speed. This dependence can be sensed at only certain roughness, e.g. at highway quality it is less dependent.

That way the investigation of the possible relations is inevitable.

It is obvious that among the input signals – determining the stresses – the road quality is excessively important. We can characterise the road quality by roughness, unevenness, peak to peak values, their largeness, occurrence frequency, and other parameters.

In other words in this meaning the road can be described by its macro- and micro-geometry. The road quality is deteriorating the micro-geometry of it is changing during its use by the traffic.

The value of the generated stresses depends on the road unevenness and the speed of the vehicles, and on the contrary the road quality has an effect on the speed, we can say that the driver automatically chooses the proper speed, the extreme behaviours are not typical. Of course the intensity of the manoeuvres – turning, braking, accelerating – are depending on the road quality too.

We can classify the roads from different viewpoints, the different road quality groups can be determined, the occurrence probability of this group can be defined.

The actual traffic conditions are deterministic in the meaning of stress state, it is enough to refer only to the speed, to the acceleration.

It is necessary to mention the technical condition of the vehicle, the aggravation of the technical condition, because the response of the vehicle to the excitations, the generated stress in the vehicle depends on its technical condition. Let us tell an example, the vehicle suspension – the condition of the springs, shock absorbers, tyre pressure, etc. – modifies the input signals in the form of transfer function in magnitude, phase and frequency. The transfer function depends on the path travelled by the input signals as well.

We have to note, that only the character of the transfer function can be generalised, we have to define its modifying effect – in amplitude, phase and frequency – from point to point of the vehicle structure. As it was mentioned the transfer function depends on input signals road quality, vehicle speed, load, technical condition, this way it cannot be considered as unchangeable function.

The road condition can be simulated by test tracks which are having the road quality characters in their occurrence probability, this way we can use the tracks for accelerated service life estimation. There are tests with special aim, e.g. suspension analysis, the effect of excessive load, not to mention corrosion and other special tests.

We can say that the input side/input signals can be determined according to the requirements, and can be used as model building elements.

The output signals are deformation, mechanical stress, these signals are used for the calculation of structure geometry, at the end of the design process for the expectable/probable service life.

This one is an undoubtful simplification, because we have not considered the material properties, the manufacturing technology and other factors which are determining the realised stress, through this the service life.

The first step is to outline a general, base conception, which can be refined/improved through each of the phases of design, by the consideration of the choice of materials, machining, manufacturing processes.

3. Mathematical Model

There are different principles, to set the dimensions, considering the maximum load, standard load, focusing on the fatigue process, on the service life, designing fail-safe, damage tolerance structure.

The choice between the different principles sometimes depends on the phases of design, in the preliminary phase it is enough to consider the maximum load, when entering into particulars the service life comes to the focal point, another approach is applied at accident analysis.

The guideline of the choices of the principles for setting the geometry of the structure elements is the knowledge of their role in the structure, the load exerted on them, the required service life, safety, only the main factors [1].

Once the principle is applied, the basic requirements are to know the quantitative and qualitative properties of the loads, to have a representative load history, for deducing the characteristic values [2, 3, 4].

In the case of vehicles the dominant failure is related to the metal fatigue. Our goal is to present a possible method designing for fatigue and for load spectrum, by the determination of stress level crossing numbers.

The load is – varying in magnitude, frequency phase versus time – resulting material fatigue and failure, damage.

It was experienced that at the usual structural materials there is a stress limit at which the service life is infinite at given probability. At the beginning of fatigue tests and analysis some important questions have arisen, namely the influence of the mean stress, the heat treatment, manufacturing parameters, etc. The parameters of stress – service life curve have been determined, the type of the distribution has been defined [5]. The fatigue tests were performed with constant stress amplitude.

It was pressing to find a way to describe the fatigue process at those cases, when the load history cannot be substituted by constant stress amplitude, i.e. to find an universal method for those cases when the load varies stochastically. In these cases it was necessary to set a dividing line, the value of it is the fatigue limit, under this limit the stresses do not induce damage, above that the damage happened. The question is the seriousness of the above limit loads/stresses in the viewpoint of damage, the remaining service life, at the same time the number and the magnitude of each stress crossing the fatigue limit and a workable hypothesis to define the stress distribution by counting the preset stress level crossing numbers.

We can divide the damage process into phases in different ways adding that any classification may induce dispute. If we divide the damage process into two phases namely the development of macro crack, then the crack propagation phase fracture – the macro crack cannot be defined with proper precision – it is understandable that a stress below the fatigue limit can cause damage.

The load – as it emerges from the previous ones – is a multi-variable function, varying stochastically/continuously in time, its value registered at a given time stochastic variable, such way it can be described by distribution function.

Before services life calculation we are setting stress levels and counting those events when the varying values of the load history – expressed in stress and plotted in stress – time diagram – cross these preset stress levels.

In a Wöhler – with given probability – curve endurance/fracture numbers are belonging to these preset stress levels.

If we – at a given stress level – do not reach the endurance limit i.e. the probe has not broken, we have not used – only a fraction of – the total service life. The test can be continued either at an increased or decreasing stress level for a given time, load cycle. (Time could be proportional of the cycle number). If the probe did not break, we have not consumed the total service life, we can continue the test again according to the above mentioned conditions until failure/fracture.

The load history is an instacioner stochastic process. For the approximate mathematical model this instacioner process divided into stacioner sub-processes, i.e. it is supposed that the recorded set of data has the properties of stacioner time-series, in other words the statistical parameters of the load history are independent of time, the load history can be represented by given data series with adequate length, and reflect all the expectable loads. The load history can be treated as an ergodic process, the statistical parameters can be derived unambiguously from a time interval with adequate length.

We have to define the technical condition of the vehicle, its subparts with precision. The parameters of the suspension – shock absorbers, springs, silent blocks – are forming the transfer function. During the service the initial value and characteristic of these parameters of the suspension are changing, until their replacement or repair.

In case of service life determination we have to consider the altered parameters of the suspension, because the excitation (road, traffic conditions, etc.), load, transfer function (suspension, load path) determine – at a given point – the stress, through it the expectable service life. By the use of maintenance strategies the parameter values can be confined in a defined intervallum.

The mathematical model therefore is a series of approximate models, which can handle a stacioner, ergodic load history with defined transfer function. (The pay load (mass) is an element of the model, with its own damping and spring properties, as passengers on buses).

The sum of the ratio of the level crossing numbers of the load history numbers according to the Miner hypothesis is one [6]. (There are modified forms of the Miner hypothesis e.g. when the ratios are raised on power, etc).

If we could determine the kind/type of distribution of the level crossing numbers the applied mathematical model can be handled easily.

3.1. Density Function of the Stress Level Crossing Numbers

The possible different mathematical methods have already been mentioned. One of the methods was when the fatigue limit has been considered, i.e. the geometrical dimensions have been set according to this stress level. The application of this method in same cases results overdimensioning, because independently of the number of the stress peak values, occurrence they – i.e. the peak values – have to be under fatigue limit.

The other method is to determine the service life. In this case the stress oversteppings – the stress more than the fatigue limit – have been permitted.

In this case constant stress levels between the load history peak – maximum and minimum – values have been set, and the level crossing numbers (how many times the constant stress levels have been crossed by the load history) are counted.

Fatigue life numbers are belonging to the same stress levels on the Wöhler curve. As it was mentioned the sum of the ratios of the counted and the Wöhler curve numbers have to be according to the Miner hypothesis.

For the application of this method we need to know the stress level crossing numbers, on the other side a Wöhler curve suited for comparison.

The stress level crossing numbers can be counted by measuring instrument. Knowing these numbers the next step is the determination of their function. The lower limit of this function is equal to the fatigue – C_*–limit of the corresponding Wöhler curve, which means that the stresses which are under the fatigue limit can be neglected, their upper limit is the elastic of the structural material. If we define the upper limit – after apt consideration – below the elastic limit we have a certain safety margin.

The design is an iterative process. In our case the stress is decreasing or increasing with the increase or decrease of the geometrical dimensions. (We are shifting the distribution function of the level crossing numbers parallel to the stress/ordinate axis), this way there will be stresses which – in this iterative step – are getting above or below the Wöhler curve fatigue limit, respectively.

The stresses of the vehicle structures viewing from the 'excitation side' – in statistical meaning – are depending on the categories of roads, the mode of operation, the travel speed and the parameters of the load, shortly on the condition parameters. It denotes the possible numbers of condition parameters, i $(1 \leq i \leq I)$ is the index belonging to the different conditions.

Further on for the model construction the followings are accepted, ... [7] [8]: let us divide the road – travelled by our vehicle – into intervals, in which the road category and the mode of operation can be considered as constant. Between these road intervals the stochastic transition, and the stochastic length of this road intervals can be described by the semi-Markov process. It can be expressed by the P_{ij} transition probability and by the $G_{ij}(x)$ distribution functions. (P_{ij} is the transition probability expressing the probability of getting from the ith condition into the jth one, while $G_{ij}(x)$ refers to the length of the road interval – or its equivalent lengths of time – of the vehicle has been in the jth condition, presuming that the previous condition was the ith one. By using the given conditions (using the properties of the semi-Markov process) we can determine with P_{ij} and $G_{ij}(x)$ the percentage of ith condition related to the total road length – after a sufficiently long travel – and it is denoted by q_i.

At a given point of the vehicle structure the average stress level crossing numbers, referring to the whole lifetime and unit road length can be written

$$N^n = \sum_{i=1}^{I} q_i N_i^n,$$

where N_i^n denotes the average stress level crossing numbers at stress level n, in ith condition.

Experience proves, that the road profile process of a given road category can be described by a stacioner Gauss process, which can be characterised by its spectral density function. Accepting the above mentioned ones and using them as a starting point it can be proved that at a constant speed and load (more precisely load distribution) – in a given mode of operation and travelling on a given road category – the values of the mechanical stress at a given point complying with the stacioner Gauss process, can be calculated in the knowledge of their spectral density function. Further on it has been supposed that the road profiles, the travelling speeds and the load conditions are independent of the length of road intervals and their previous values having been observed on the proceeding road interval.

We can divide the road into intervals where the speed is constant and where it is inconstant. We are dealing with the constant speed states. The transient parts can be neglected or possibly can be tackled as additives.

It is supposed when the vehicle is in ith condition the process function describing its speed and loading in narrower meaning is stacioner, $F_i(x, y)$ denotes its distribution function.

At given i condition of the vehicle and constant x speed, and y load $N_i^n(x, y)$ means the average stress level crossing numbers at a u stress level.

At the previously mentioned conditions

$$N_i^n = \int_0^\infty \int_0^\infty N_i^n(x, y)\,\mathrm{d}F_i(x, y).$$

Let us begin with continual approaches of this integral. For this purpose divide the reasonable speed and load intervallum into subintervallums.

$$\left\{\Delta_{v,a},\ 1 \le a \le K\right\}, \quad \left\{\Delta_{z,b},\ 1 \le b \le L\right\},$$

where K and L denote the numbers of subintervallums, respectively.

Let us take from each of the speed and load intervallum a point x_a and y_b $(1 \le a \le K\ 1 \le b \le L)$ and $r_{a,b}^{(i)}$ denotes the probability, that a random speed and load (in magnitude) is inside in $\Delta_{v,a}$ and $\Delta_{z,b}$ intervallum, respectively.

This process is an approximation of distribution function of the simultaneous speed and load process $F_{v,z}^{(i)}(x, y)$ with a two dimensional discrete distribution

$$\left\{(x_a, y_b), r_{a,b}^{(i)},\ 1 \le a \le K,\ 1 \le b \le L\right\}.$$

Coming from the above written the average stress crossing number – belonging to the given condition $i(1 \le i \le I)$ of the vehicle can be approached by a summation

$$N_i^n \approx \sum_{a=1}^{K} \sum_{b=1}^{L} r_{a,b}^{(i)} N_i^n\,(x_a, x_b)\,.$$

Let us see the $N_i^n\ (x_a, y_b)$ stress level crossing number. At given points of the vehicle at x_a, y_b values the loading process can be discussed by a stacioner Gauss process with $\varphi_{i,a,b}(\omega)$ spectral density function. The $\varphi_{i,a,b}(\omega)$ spectral density function can be expressed by vehicle parameters, by the values of x_a, y_b and by the spectral density function of the road profile process in the ith condition.

Such way according to the Rice formula the stress level crossing numbers are:

$$N_i^n(x_a, y_b) = \frac{1}{2\pi}\frac{(\mu_{i,a,b})^{1/2}}{(\lambda_{i,a,b})^{1/2}}\exp\left\{-\frac{u^2}{2\lambda_{i,a,b}}\right\}$$

where

$$\lambda_{i,a,b} = \int_0^\infty \varphi_{i,a,b}(\omega)\,\mathrm{d}\omega, \qquad \mu_{i,a,b} = \int_0^\infty \omega^2\varphi_{i,a,b}(\omega)\,\mathrm{d}\omega$$

$\lambda_{i,a,b}$is the standard derivation of the stacioner Gauss process with $\varphi_{i,a,b}(\omega)$ spectral density function, while $\mu_{i,a,b}$ is the second spectral momentum of the Gauss process.

Summing up our results, the average stress level crossing number (as an approximation) is

$$N^n \approx \overline{N}(n) = \sum_{i=1}^{I}\sum_{a=1}^{K}\sum_{b=1}^{L} q_i r_{a,b}^{(i)}\frac{1}{2\pi}\frac{(\mu_{i,a,b})^{1/2}}{(\lambda_{i,a,b})^{1/2}}\exp\left\{-\frac{u^2}{2\lambda_{i,a,b}}\right\}.$$

For the further analysis the followings will be introduced. Arranging according to their magnitude the different $M = I \cdot K \cdot L$ $\lambda_{i,a,b}$ values – belong to (i, a, b) indexes – and σ_m denote the square root – in sequence – the m – th number (the deviation of the stress process belongs to the m index), and c_m is a constant value

$$c_m = q_i r_{a,b}^{(i)}\frac{1}{2\pi}\frac{(\mu_{i,a,b})^{1/2}}{(\lambda_{i,a,b})^{1/2}}.$$

Then it is obvious, that

$$\sigma_1 \le \sigma_2 \le \dots \sigma_M \quad \text{and} \quad \overline{N}(n) = \sum_{m=1}^{M} c_m \exp\left\{-u^2/\left(2\sigma_m^2\right)\right\}.$$

We can get the density function of the stress level crossing numbers as follows:

$\varphi(w)$ denotes the density function of the standard normal distribution, i.e.

$$\varphi(w) = \frac{1}{\sqrt{2\pi}}e^{-x^2/2}, \qquad -\infty < w < \infty.$$

With the introduced designation

$$\overline{N}(n) = \sum_{m=1}^{M} d_m \frac{1}{\sigma_m}\varphi(u/\sigma_m), \quad \text{where} \quad d_m = c_m\sqrt{2\pi}\sigma_m$$

positive constants.

The function $\overline{N}(n)$ is the superimposition of the different $(d_m/\sigma_m)\varphi(u/\sigma_m)$ functions with m indexes. It can be seen, in the important – in the view of our investigation – $C_x \leq u < \infty$ domain the behaviour of the function

$$\overline{N}(n) = \sum_{m=1}^{M} d_m \frac{1}{\sigma_m} e^{-u^2/(2\sigma_m^2)}$$

does not depend on d_m and σ_m equally.

Since $e^{-x^2/(2\sigma^2)}$ $(\sigma > 0)$ function is monotonously decreasing to the limit 0, when $|x| \to \infty$, such way we can neglect those $d_m \frac{1}{\sigma_m} e^{-C_*^2/(2\sigma_m^2)}$ parts in the $\overline{N}(n)$ function which has relatively small values, where C_* is the lower limit. This provides possibility to separate the dominant members determining the stress level crossing numbers.

With the knowledge of the density and distribution function of the stress level crossing numbers a Wöhler curve will be selected, which curve fulfils the requirement of cumulative damage. (The values of the Wöhler curve is modified by the material manufacturing technologies, technological parameters, the role of the machine element in the construction, etc.)

The question is when the mathematical method for service life determination is used whether the structure endures the given load spectrum/load history, without damage.

An open/unanswered question is the steps of the calculation process when there is no way to compare the load history with a single Wöhler curve. In the case of dimensioning to the fatigue limit there are diagrams as Smith and equivalents with it. For the illustration of the raised question it is not exceptional, that the unidirectional increase/decrease of the load alters the sign of stress, in other words the stress spectrum cannot be compared with a single Wöhler curve.

4. Summary

The vehicle structures are subjected to fatigue load. The geometrical dimensions can be set by dimensioning for fatigue or for service life. In case of service life determination i.e. using the principle of cumulative damage, a representative load history is compared with a Wöhler curve, absolutely necessary to know the distribution function of the stress level crossing numbers.

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