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NECESSITY OF DYNAMIC MODEL CONSTRUCTION AND SIMULATION FOR THE SIZING OF STRUCTURES

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ABSTRACT

As the first in a series of lectures the article presents the problem of sizing procedures in mechanical engineering, which extends to determination of loadings and structure characteristics and determination of the loading amplitudes absolutely necessary for sizing to counter fatigue. The paper makes it clear that without dynamic tests (simulation), even in the case of the most accurate models unusable structures could be designed, which would only come to light during trial operation of the constructed equipment under operation.
Further parts of the article series present the dynamic models, then the simulation programmes based on these, and finally the process and result of a simulation test by means of a concrete example.

KEYWORDS*: sizing procedures, loadings characteristics, loading amplitudes*

1. INTRODUCTION

When sizing the mechanical structures and their elements the most important requirement that must be satisfied, is that the given component should operate for an established period without deterioration.
The structure is reliable if the safety factor

$$n = \frac{H_{(t)}}{T_{(t)}} \geq 1 \tag{1}$$

where: $H_{(t)}$ loading limit
$T_{(t)}$ loading

The difficulty is caused by the fact that in general the loading limit, the loading and due to this, the safety factor are functions of time.
This requirement can be satisfied with the greatest assurance with loads that are constant with time.

2. SIZING FOR LOADING CONSTANT WITH TIME

The load bearing capacity of structures under static loading is the deformation limit, which is given in the stress form.

$$n = \frac{H_n}{T_n} = \frac{\delta R_{eH}}{\alpha \sigma_{ideális}} \quad (2)$$

where:

δ - yield limit-relative number

α - form factor

σ_{ideal} - Stress arising in **krm??**, without notching.

This relation is very applicable, thus the loading can be regarded as static up to a load cycle number of 10^4. In this case the loading can be determined with great accuracy, the values of form factor determined by experiments are recorded in nomograms. The structure characteristic is partly a function of material characteristics and partly of yield limit-relation, which can be established in the knowledge of the form factor.

In the case of complex loading the knowledge of multi-axial stress condition is not suitable for direct sizing. Therefore such a single-axis stress condition (equivalent stress) must be established, which agrees in effect with the stress actually occurring (Mohr, H.M.H. theory). In this case the yield limit-relation and the form factor must be determined to suit the complex loading.

In summary it can be established that the accuracy of sizing structures under static loading is determined by the material characteristics established in material science and the accuracy of equations applied in mechanics.

3. QUESTIONS TO BE CLARIFIED IN THE CASE OF LOADINGS CONSTANT WITH TIME

The majority of structures are exposed to loads changing with time. The first problem is to clarify what, and in what measure, causes the change of loading with time. Most frequently the following cases occur:

- uneven torque provision or demand (operating characteristics of driving and driven machines);
- the dynamic properties of drive chain elements;
- a characteristic of the executed technological process;
- frequent start-up…etc.

The listed effects appear as an exciting effect in a flexible system susceptible to oscillation. The condition for accuracy of sizing is that the loading changing with time is known with suitable accuracy.

Methods of determining the loadings:

- BY MEASUREMENT: the most accurate method, can be carried out in possession of measuring implements and procedures, only applicable on finished structures, thus cannot be used in preliminary designing;
- BY ESTIMATION: using experience gained from different machines, but operating with similar parameters;
- Starting out from the STATIC CASE (nominal capacity), constructing a model with loading changing with time;
- BY CALCULATION: the loads are determined with a dynamic model, which in this case are the external loadings and other incoming data. These calculations are so time-consuming and complicated, that they can only be applied in the form of a computer programme.

Today many designing systems contain a dynamic modelling programme, which is a „black box" for the benefit of the user. Later in my paper I shall present and demonstrate the application of a simulation programme of my own development based on known mechanical models.

4. THE PROBLEMS OF SIZING DONE FOR FATIGUE

Among the methods mentioned in the previous point only the last two are applicable for preliminary sizing, but in the lack of a computer designing system the third case may be used. In the following I show the restrictions of applying this method. The actual safety of the structure's element, can be determined by the well known relation:

$$n_{(t)} = \frac{H_{(t)}}{T_{(t)}} \tag{3}$$

For construction of the loading model, besides the nominal loading, knowledge of the k_o operating factor and the k_s starting factor is necessary. These values are dependent on the driving and driven machine, thus take account of the technological process executed by the drive chain. Their values have been determined by measurement in the case of various machine groups, then compiled in technical principles. The amplitude and starting overload values for the model constructed in this way can be read in figure 1.

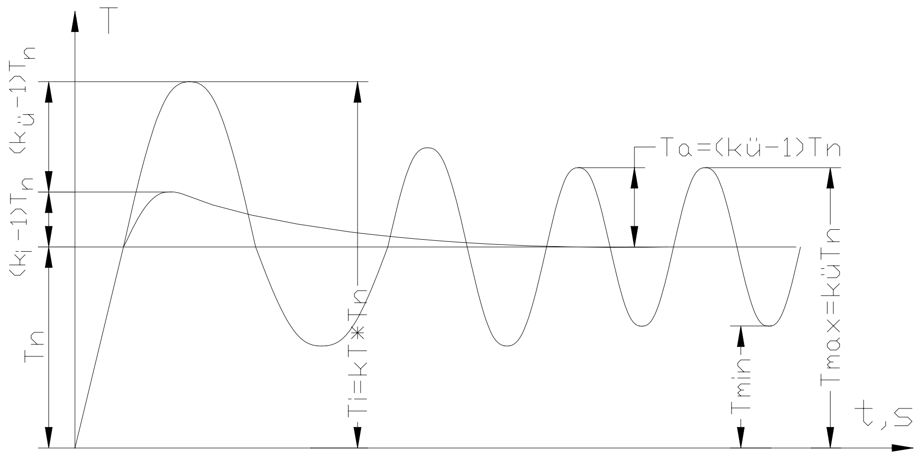

Fig. 1. The loading amplitude and the starting overload value

$$T_a=(k_o-1)T_n \tag{4}$$

$$T_s=k_TT_n \tag{5}$$

where: k_T – overloading factor

$$k_T = k_s\, k_o \qquad (6)$$

The loading changing with time in the constant operating state:

$$T_{(t)} = T_n + T_a \sin\omega t \qquad (7)$$

where: ω – cycle frequency of the exciting effects

In knowledge of the loadings the bearing force diagrams can be drawn and the medium and amplitude stress aroused in individual cross-sections can be calculated: σ_m and σ_a

If the loading cycle number (life) of the sized component:

- is planned between N = 10^4-10^7., then with determined survival probability the limiting fatigue stress relating to the given life can be established on the basis of the Wöhler curve. Here is included the selection of roller bearings and for example the sizing of individual aeroplane components;
- N>10^7, the sizing must be done against fatigue. The limiting fatigue stress necessary for sizing against fatigue: R_{Da} is most frequently determined with the help of the Smith diagram.

The fatigue safety factor:

$$n_f = \frac{k_1 k_2}{\beta} R_{Da} \frac{1}{\sigma_a} \qquad (8)$$

where:

β – groove factor
k_1 – surface quality factor
k_2 – dimension factor

The Smith diagram established for the given basic material by experiment is only directly valid for test bodies, therefore the geometric construction of the components and the bearing force mode are taken into account with selection of the β groove factor, the component dimension and surface quality with the k_2 dimension, and k_1 surface quality factors. These factors were established by experiment and with their application we obtain a safety diagram characteristic for a given component construction with reduced area. The uncertainty in determining the safety factor is caused by lack of knowledge regarding temporal course of the loading. The safety factor value expresses geometrically, by what path the point P equivalent to the stress state aroused under the given load, will appear on the safety area onto the limiting curve.
Although in the general case the amplitude stress (σ_a = const.), none of the models relating to the mean stress (σ_m = const.) and their ratio, $\left(\frac{\sigma_a}{\sigma_m} = const.\right)$ completely fulfils this, we apply the $\frac{\sigma_a}{\sigma_m} = const.$ approach with the smallest inaccuracy (figure 2.).

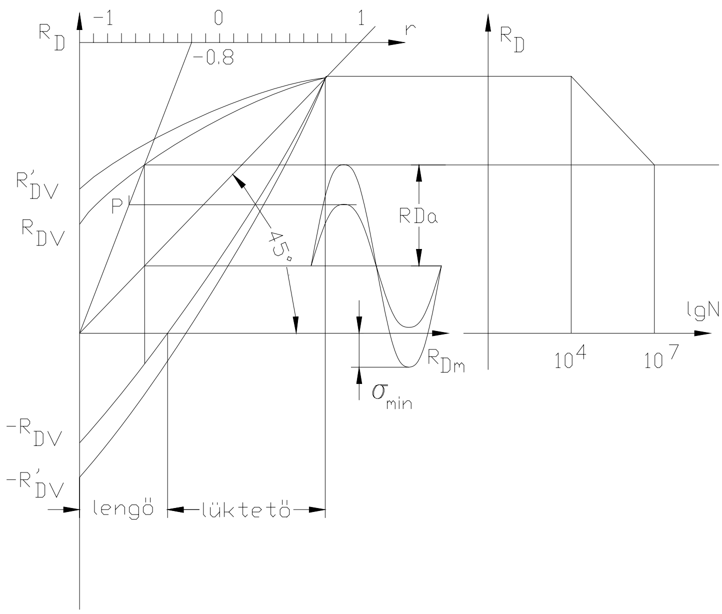

Figure 2. Smith fatigue diagram

In the case of complex bearing force changing with time, the Smith diagram constructed for single-axis stress state can be applied with close approximation if the reduced mean and amplitude stresses and groove factors are established.

5. SUMMARY

In the course of preliminary designing, even the most accurate loading model and most carefully executed calculation will only be valid for a structural element „behaving statically". As is well known, every structure (even the human body as well) has its natural- oscillation frequency). In simple cases these natural-oscillation frequencies can be easily calculated and measured, a good example of which is a cantilever spring.
When constructing the loading model, in the $T_{(t)} = T_n + T_a \sin \omega t$ relation the ω is the load cycle frequency, (is known in the case of an electric motor-driven drive chain) but as an exciting frequency is in many cases stochastic. The frequency of gusts of wind acting on a bridge structure are a good example of this. In the case where the structure's own angular frequency α, and the excitement angular frequency ω coincide or almost coincide, resonance could be developed. In this case, as in every flexible element energy is accumulated. If sufficient time is available, then it will vibrate, oscillate with ever-increasing amplitude until the fracture occurs in the critical cross-section. Naturally there are some such mechanical appliances, for example vibrators and vibrating tables where the exciting frequency is tuned to match the appliance's natural-frequency, but in the general resonance should be avoided.
Thus the resonance can only be avoided if the exciting and natural-frequencies are tuned away from each other. Since in general the exciting frequencies are given, the solution often means tuning the natural-frequency away from this.
The natural frequencies of structures and drive chains are functions of very many parameters and can be determined with extremely complicated calculation processes. If the natural

frequency is not known at the preliminary sizing, the resonance cannot be excluded therefore the loadings cannot be modelled with complete safety.

6. RECCOMMENDATION FOR THE SOLUTION

The preliminary sizing and checking procedures applied in designing practise are not capable of dealing with problems appearing in connection with occurrence of resonance. The only solution is represented by dynamic modelling of the structures, with the help of which the natural frequency of the system can be determines, and then the loadings can be determined from the value of the exciting and natural frequencies compared to each other. In the following paper I outline the steps and problems of dynamic model construction, indicating many possible directions of research.

7. LITERATURE USED

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