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## A BRIEF OVERVIEW ABOUT THE DEVELOPMENT OF TORSIONAL VIBRATION CALCULATION AND EDUCATION OF METHODS FOR THEIR CALCULATION

**Summary.** Torsional vibration calculation (TVC) is among the basic calculations that are required to support propulsion projects for various vehicles, ships and construction machines. A number of powerful software packages for these calculations already exists. However, the need to respect the physical properties of propulsion systems that are more complex than before has arisen. At the same time, knowledge about system properties and the capabilities of computing systems are also growing, resulting in an increase in new software systems, which could be used for these calculations. In this paper, these new trends are briefly described, with attention paid not only to practical use, but above all to how and to what extent these themes should be presented to students.

**Keywords:** propulsion systems; torsional vibration calculation; trends in development of torsional vibration calculation; simulation methods; GT-Power

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## 1. INTRODUCTION

TVC is among the basic calculations that are required to support propulsion projects for vehicles, ships and construction machines. These calculations have been known and applied for more than 100 years initially in response to ship shaft snapping, which started with use of piston steam machines in about 1870.

More calculation methods have been developed since the 19th century and used for TVC. These methods are described in detail in numerous publications, as well as currently used in practical settings.

The basic principles of torsional vibration are naturally presented on basic educational courses on machinery dynamics. In the case of more advanced courses for students studying fields related to the construction of piston engines and vehicles, torsional vibration problems are explained in much more detail, with an emphasis on the connection between basic mechanical vibrations and the practical application of TVC to real propulsion systems. Students find this interesting, as they directly see how knowledge from pure theory is reflected and used in praxis.

For the calculation of torsional vibrations, methods are employed, which are the basis for commercial software. There are even methods described in “bibles” in this field, such as [1,2,3]. Typical torsional vibration programs, which are equipped not only with proven computing procedures but also with subroutines enabling easy and fast input and the economic output of results (user-friendly), are used by ship classification societies, for example, “Det Norske Veritas” [4].

Let us not forget the last standard [5], which gives a detailed overview of the whole issue.

At present, simulation methods are increasingly being applied for TVC purposes, which must also be introduced to students.

The purpose of this paper is to introduce to involved experts the scope of the content presented to students on courses covering TVC, as well as the latest developments in this field.

## 2. BASIC PRINCIPLE OF THE COURSES

The lectures related to TVC are based on the fact that, if professional computations are made, it is also necessary to use one of the professional software packages. In the manuals for such packages, there is usually enough information on how to use them. However, there is often a lack of information on the theoretical foundation of the software, which often means that less experienced users view the software as a “black box”. For this reason, the theoretical basis of TVC and the basic methods for its applications should be explained.

It should be also taken in account that not every workplace will have access to highly sophisticated software, bought at considerable expensive. As such, it is important to recognize that it is possible to perform a number of less demanding calculations using simpler means, such Excel.

## 3. NATURAL FREQUENCY CALCULATION

Basic information about an oscillating system facilitates the calculation of natural frequencies and vibratory mode shapes (normal elastic curves), which correspond to them.

For this purpose, the Holzer method [6] is presented, which, despite being first published in 1907, is easy to apply due to simple algorithmization. In addition, this method, based on the search for equality between kinetic and potential energy, gives a good explanation of the physical principle of resonant phenomena.

The second method for the calculation of natural frequencies, as presented in lectures, is based on seeking out frequencies that correspond to the state, when the determinant of the equation of motion reaches the value of 0. The calculation is again easy to carry out using matrix algebra and macroprogramming, both of which are parts of Excel.

For users with MATLAB at their disposal, it is naturally easy to use the subroutine “eig”.

## **4. FORCED VIBRATION CALCULATION**

### **4.1. Steady states, linear systems**

TVC, until recently, was based on the frequency domain approach and focused primarily on steady-state solutions.

In lectures, the so-called “direct method” is explained, in which the system of differential equations is transferred, using the assumed form of the solution (sinus), in a system of algebraic equations, which is then easily solved using the MATLAB equation solver.

The method is, in principle, suitable for solving linear differential equations. If some weak non-linearities are present in the system, which can be replaced by their equivalent linear values, such as equivalent linear stiffness or equivalent linear damping, and when these non-linearities are dependent on the oscillation frequency or the instantaneous mean load in the connections between masses, these non-linearities can also be respected.

In lectures, the transfer matrix method is also explained [7]. The method resolves physical vibration problems in a similar way to the “direct method”; the same applies to the steady-state vibration of linear systems. However, the programming is more transparent, uses smaller matrixes and is therefore more suitable for systems with fewer degrees of freedom and also for smaller computers equipped with simple software. In addition, the principle can be applied not only to torsional vibration but also to a combination of different types of oscillation, such as linear or bending oscillation. Therefore, an acquaintance with this method is useful.

Another common method is the “modal method”, which transfers the original equation of motion to a new system in which every equation only corresponds to one mode of vibration. This method, as described, for example, by Ker Wilson [1] or in [2], is commonly applied, even if it is not quite exact for systems with stronger damping. In fact, it uses the results of the natural frequency calculations of an undamped system to calculate forced vibration. However, this method has a number of advantages, particularly in terms of low demand for computing technique. There is also plenty of experience with this method. Nevertheless, the method is especially included in lectures because it significantly helps us to understand what happens in the system when it oscillates and the effect of excitation, damping, mass and stiffness, when they are located in certain positions in the oscillating system.

### **4.1. Transition states, non-linear systems**

To solve transient states in systems with non-linear equations of motion or a combination of both, it is necessary to default to the solution in the time domain. This means it is necessary to use a numerical integration method [8].

Naturally and generally in these cases, it is the most common and most accessible to use the simulation and model-based system Simulink, which is integrated with MATLAB.

For the application of simulation calculations, particular in the case of dynamics in drive lines, Latchet's book [9] could be very helpful.

In recent years, this approach has been increasingly successful in the simulation of various processes including the dynamics of drive lines using the SimulationX software produced by the ESI ITI company from Dresden (see *Conference Proceedings* [10]).

A recent application of SimulationX, in connection with the model description language Modelica, was described by D. Grimm from Daimler AG in his paper in [10]. Similar articles e.g., [11] have been produced by MAN B&W, while [12,13] describes the selection of calculating software for the Croatian Register of Shipping.

The aforementioned packages are already far more adaptable to professional use. Efforts have also focused on the rapid calculation of alternatives, offering an opportunity to optimize design parameters quickly and effectively [14].

## 5. SIMULATION, MODELING IN GT-POWER

Rather than SimulationX, another powerful simulation software package called GT-Power is at the disposal of the Czech Technical University in Prague. The software is managed and distributed by the US company, Gamma Technologies, from Westmont, IL.

GT-Power is the industry-standard engine performance simulation package, which is used to predict engine performance quantities, such as power, torque, volumetric efficiency, fuel consumption and turbocharger performance. For problems connected with torsional vibration, GT-Power can facilitate the following calculations:

- Crankshaft torsional vibrations (time and frequency domain)
- Viscous and rubber dampers
- Engine unbalanced force moments, balance shafts
- Three-dimensional block vibrations and mounting system analysis, vibration isolators

It is clear that the calculation possibilities are considerably wider in this regard than for previous non-simulation methods. Calculations, as can be seen, also include such effects that were not previously considered but are nevertheless related to alternating torques and to torsional vibrations, which is evident, for example, in the case of oscillations of the entire engine.

Another undeniable advantage is that, if the excitation effects of working cycles in individual cylinders (tangential pressures) are not known in advance, then it is possible to calculate them using GT-Power. The introduction of more sophisticated models for the stiffness and damping of elastic members, as well as for vibration damping, involving vibration dampers and pendulum eliminators, is one of the advantages of the system.

Last but not least, GT-Power allows us to respect the influence of engine regulation, which in turn facilitates a solution to problems such as diesel engine "hunting" when idle.

These are all reasons why GT-Power calculations are included in the learning process.

## 6. COMPARISON OF DIFFERENT METHODS OF TORSIONAL VIBRATION CALCULATION

Although it would appear that TVC and its results, using the different methods listed above, must be the same; in practice, however, the matter is not so simple.

The main reason is that each method works in some cases with slightly different models of mass-stiffness system components, such as models of dynamic stiffness or damping. This is especially true of computation in the frequency domain.

On the other hand, numerical integration allows us to more accurately respect the dynamic properties of system elements compared with simple equivalent linearization. In turn, we can use more sophisticated models of elastic and damping elements, such as those described in [15].

Another problem concerns the phase shifts of each harmonic response component, which may be affected by the damping present in the system. Inaccurate phase shifts could influence the synthesis values of the torsional angle and load ([16], Chapter 4.19). Therefore, only scalar sums should be considered in these cases.

To make the process of entering input values into the program and clarify the way in which to understand the calculation results, TVC was carried out using the above-described methods. Each calculation was performed on the same diesel generator assembly with an elastic coupling. Subsequently, the way in which each of these methods respects the dynamical model of the drive line was assessed, along with the difficulty in preparing the calculation and determining time necessary to perform it.

The first calculation methods, which will be mentioned further, employ the “direct” method, while the second employ “modal analysis”, both of which are programmed in MATLAB.

Both these two calculations were compared with the GT-Power calculation. For transient states, in this case the engine starting period, Simulink and GT-Power were used.

Programming with the use of the “modal method” seems to be easy and quick to perform. It looks sufficient when the calculation of an elastic coupling is necessary and when only one mode of vibration is decisive. For more complicated systems, it is necessary to take into account the fact that the phase shift between different vibratory modes is not quite correct. The calculation is based on a simplified assumption about the normal elastic curves determined for the undamped system. Therefore, the synthesis of vibration caused under different vibratory modes and by different harmonic components of excitation could involve scalar summation only, as mentioned above.

Programming using the “direct method” is slightly complicated, mainly because the extent of the resolved systems and thus the calculation are usually greater. The method is widespread and used above all as a basis for professional programs. The limitation is that it only solves stationary states and only respects certain types of weaker nonlinearities.

The use of Simulink is useful when no other software packages, specializing in non-linear and transient torsional vibration, are available. Simulink calculations, for the same drive line, produce the same results compared to GT-Power calculations, but the time necessary for the latter calculations is disproportionately higher.

## 7. SUMMARY AND CONCLUSIONS

TVC is one of the basic calculations needed for the design of drive lines. These calculations have a long tradition and therefore developed to a very good level.

When teaching students, the basic methods are firstly described to help them understand the nature and solution of the problem and to apply them using simple, but generally accessible, computer software. Afterwards, the application of existing professional software packages is shown.

However, methods are developing all the time, while a recent trend in using simulation programs is clearly visible.

They are mainly two software packages used in this field: SimulationX and GT-Power. These packages are able to solve similar problems in a similar range, to a much large extent than in the case of classic older programs.

GT-Power is available at the Czech Technical University, meaning that its students are familiar with the software, at least in terms of the basic forms of calculation.

In the course of conducting the activities mentioned in the paper, selected examples were presented, which could be solved by students in seminars.

This theme will continue with investigations into other more complicated applications of GT-Power for advanced systems, such as in the form of a solution to a system with a two-mass flywheel or with a pendulum torsional vibration eliminator.

Nevertheless, improvements in the calculation methodology should continue to be made, but only in direct connection with the calculation of real drive lines and by comparing the calculated values with the measurement results.

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