ACTIVE DAMPING OF COMPOSITES

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THEME

Dynamic FEA with active control

KEYWORDS

Active damping, active control, composites, dynamic FE analysis, FE control elements, dynamic response in time and frequency domain, real and complex modes, optimization, sizing, shape optimization, frequency response optimization

SUMMARY

The design of lightweight structures frequently leads to the use of composite materials like carbon fibre reinforced plastics (CFRP). Due to reduction of weight CFRP structures are more susceptible to vibrations in dynamic applications. One way to damp undesirable vibrations is to use active control which combines a sensor to pick up vibration characteristics, an actuator to induce damping forces, and an appropriate control device to derive the latter from the first.

The paper describes the basics of control in FE analysis. An example of a CFRP structure with applied active damping elements is used to show the effect of control in dynamic simulations. This example is also used to demonstrate the application of optimization to actively damped composites.

1: Introduction

The design of lightweight structures frequently leads to the use of composite materials like carbon fibre reinforced plastics (CFRP). Due to reduction of weight CFRP structures are more susceptible to vibrations in dynamic applications. One way to damp undesirable vibrations is to use active control which combines a sensor to pick up vibration characteristics, an actuator to induce damping forces, and an appropriate control device to derive the latter from the first.

From a simulation point of view, predicting dynamic behaviour clearly needs to take active control into account. In order to make active control a part of Finite Element (FE) analysis a number of control elements can be provided which are used to implement the differential equations of control. For linear control devices, all standard computational methods of structural dynamics like natural vibration analysis, complex mode analysis, frequency response and time-history analysis are available. So, extension of dynamic FE analysis to actively controlled structures is provided in a very natural way.

The use of active damping raises a number of questions regarding the location of sensors and actuators or regarding the parameters of the applied controllers. These topics can be handled by optimization methods in FE analysis where, for example, the location and the parameters of controllers are the design parameters and limited amplitudes of a frequency response function are the design objectives.

The paper comprises short sections on modelling composites and modelling controllers. Then, a CFRP box girder is used to explain eigenvalue and frequency response analysis and its results for models with and without a controller. Sizing optimization is used to adapt the controller parameters to optimum damping conditions. Finally, an optimum controller position is found using shape optimization features.

2: Modelling and Analysis of CFRP Structures

Layered shell elements are usually used to model structures with CFRP material. Based on a typical FE shell structure, the stack of plies and their characteristics have to be specified in addition (see Fig. 1). Each ply has to be characterized by the ply material, the ply thickness, and the ply orientation angle. The latter is usually measured against a material reference system. The ply material can be isotropic or anisotropic, but a CFRP layer has orthotropic material properties, of course.

Composites establish a highly inhomogeneous material which is usually homogenized by extended laminate theory (e.g. see [1, 2, 3] for more details) which combines membrane, bending, and transverse shear effects. Finally, a composite material is fully anisotropic, i.e. engineering reasoning on how a structure deforms under certain load will often fail, because such anisotropic materials do not allow for easy prediction of deformation. That makes it very important to use FE analysis for such materials.

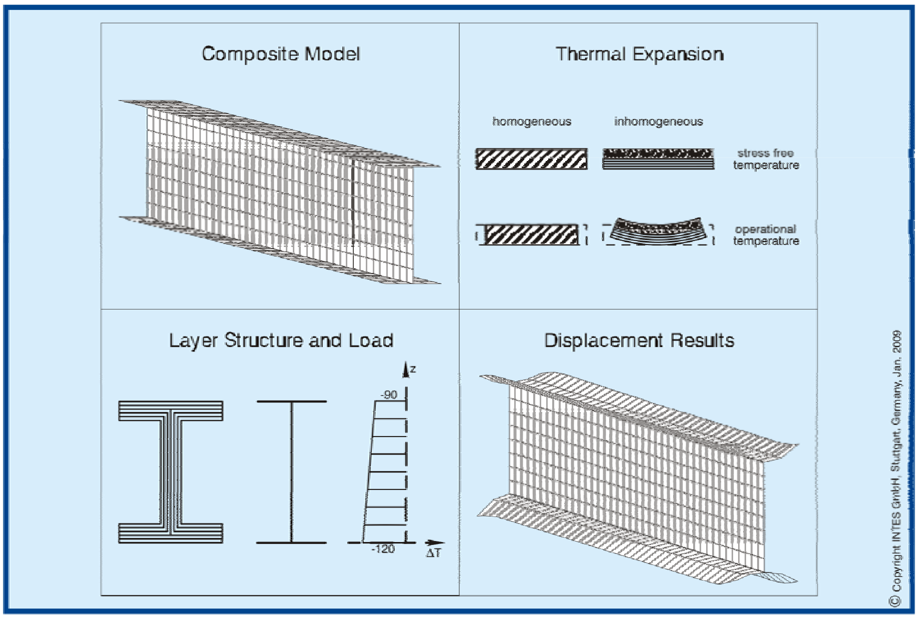
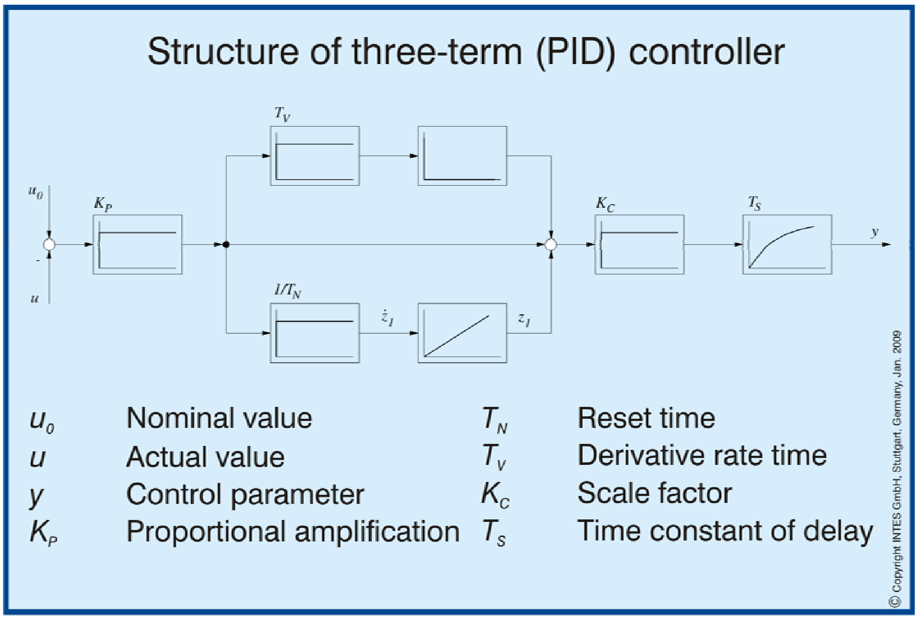


Figure 1: **General set-up and behaviour of composite shell structures**

3: Coupled Analysis of Structures with Active Control

Design and application of controllers is an art of its own right and typically not a standard working field of FE analysts. But it was proven that certain phenomena in vibration analysis of controlled structures cannot be predicted without a directly coupled analysis of structures and active control (see [4, 5, 6]). One schematic view of a simple controller is shown in Fig. 2 which shows a three-term controller (often also named as PID controller where PID stands for a proportional, an integrating, and a differentiating element of the controller).

One approach to make controllers accessible in FE calculations is to create FE control elements which e.g. represent such a three-term controller where the parameters of the controller become parameters of the control element. The integration of the constitutive differential equations of the controller is done on control element level. Hence, beyond element level, FEA software just handles matrices. This makes it very easy to integrate active control in FE analysis.

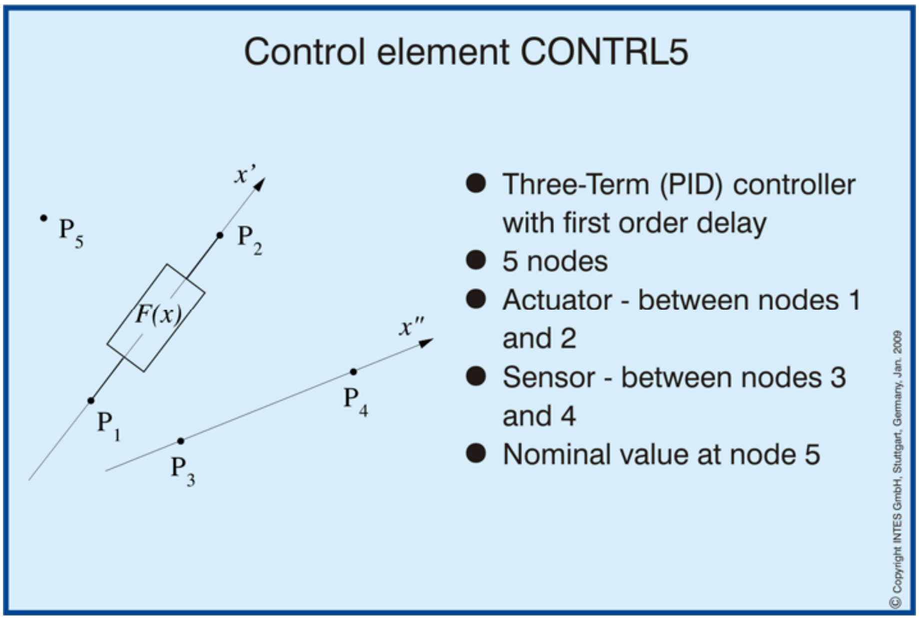


Structure of three-term (PID) controller

u_0	Nominal value	T_N	Reset time
u	Actual value	T_V	Derivative rate time
y	Control parameter	K_C	Scale factor
K_P	Proportional amplification	T_S	Time constant of delay

Figure 2: Block diagram of a three-term (PID) controller

Fig. 3 shows the FE representation of a three-term controller. The element has five nodes: Two nodes are for the representation of the actuator, two nodes are for the sensor, and one node remains for the internal state of the controller (for setting a nominal value). The location of actuator and sensor is taken from the physical location of both devices in the structural model. The location of the remaining fifth node is arbitrary.



Control element CONTRL5

- Three-Term (PID) controller with first order delay
- 5 nodes
- Actuator - between nodes 1 and 2
- Sensor - between nodes 3 and 4
- Nominal value at node 5

Figure 3: Control element CONTRL5 representing a three-term controller

In practical cases, a three-term controller may be too simple and, indeed, there are strong requests for more complicated controller structures. Although several three-term controllers can be combined to build more advanced controller structure, it became obvious that users want to have larger controller structures available through one control element only. Consequently, there are additional control elements for so-called cascade controllers which have 8 or 10 nodes. In addition, beside an integrated generation of the element matrices, the user could also provide subroutines which realize a specific control device.

Because most of such controllers are linear controllers, the integration of control elements in FEA allows the use of all standard dynamic solution methods, like real and complex vibration analysis, modal and direct response analysis in frequency and time domain. In case of nonlinear control procedures, special nonlinear control elements are available which are restricted for use in time domain, of course.

4: Vibration Control of a CFRP Box Girder

As an example, Fig. 4 shows a CFRP box girder, where the composite has eight plies in a symmetric ply stack with four different fibre orientations. The girder is fixed at one end and the girder tip is used to apply an excitation force or an initial displacement as well as to get result amplitudes to compare the controlled girder with the not-controlled one.

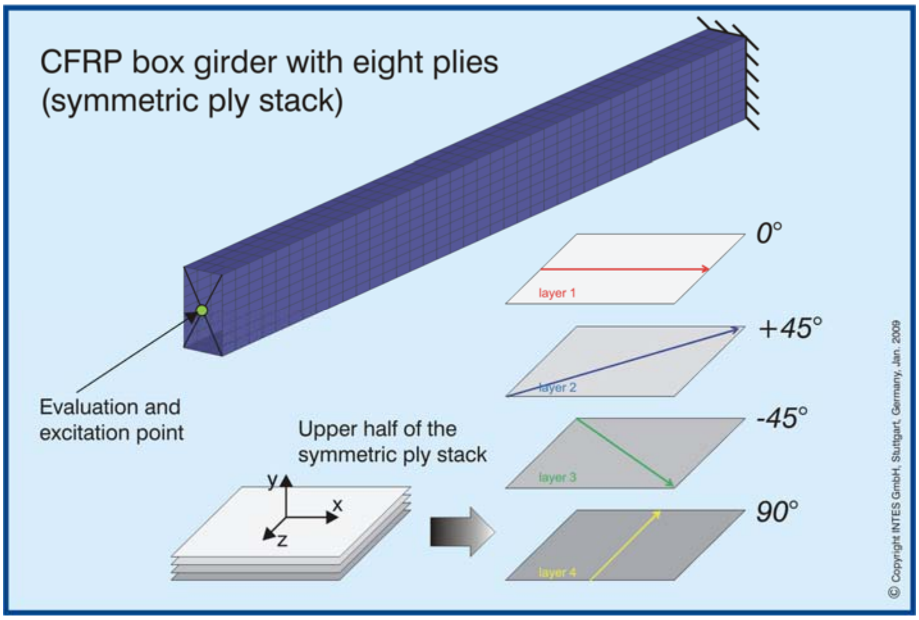


Figure 4: **CFRP box girder with 4-layer composite**

Fig. 5 shows the results of a first modal frequency response analysis without any control element. The relevant bending modes are mode 1, 4, and 10, where mode 1 is the most important mode according to the high displacement amplitude.

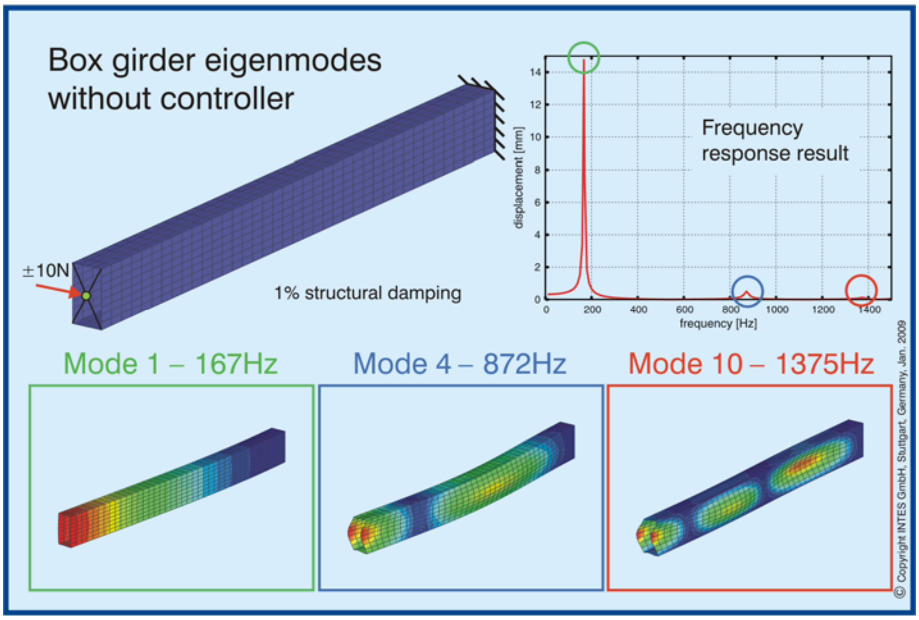
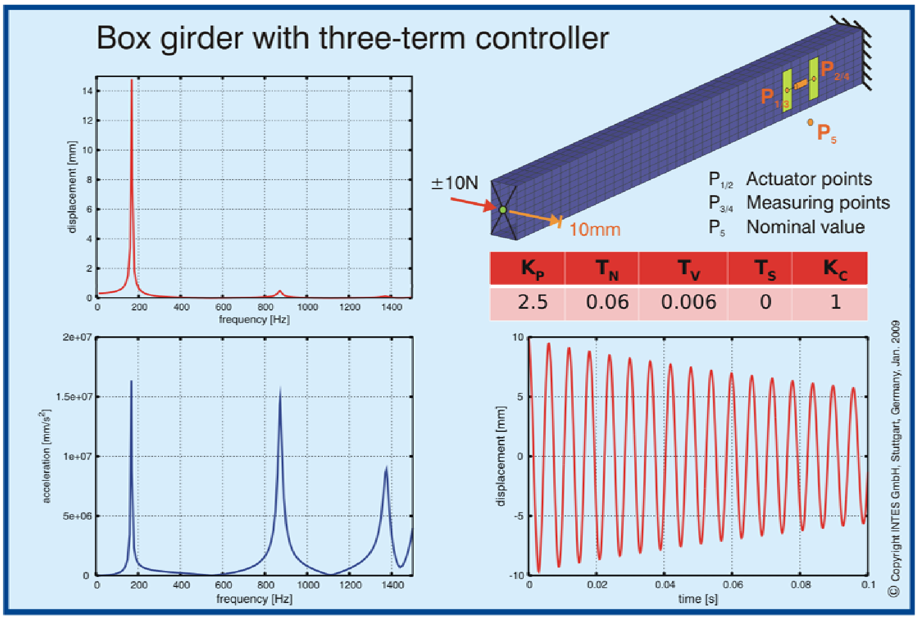


Figure 5: **Eigenvalue and frequeny response analysis without control element**

The next step is the use of a control element (as shown in Fig. 6), where only one control element is applied at one side of the girder. The actuator and sensor nodes are not connected with one single node of the structure but with element patches which are connected to the structure by MPC (multi-point constraint) conditions. In this way the real size of an actuator like a piezo-ceramic patch is taken into account.

The particular controller is modelled in such a way that the actuator and sensor nodes are the same. For simplification reasons the controller does not provide for a time delay (i.e. parameter T_S is zero). In this way, no phase difference exists between the sensor signal and the actuator operation. Although this is not true in many practical examples, it is in any case highly desirable to position sensor and actuator as close as possible.

When comparing the frequency response results with and without control element (see Figures 5 and 6) there is no significant difference in displacement amplitudes. The conclusion would be that a controller is useless or that the controller parameters are not adequately selected.

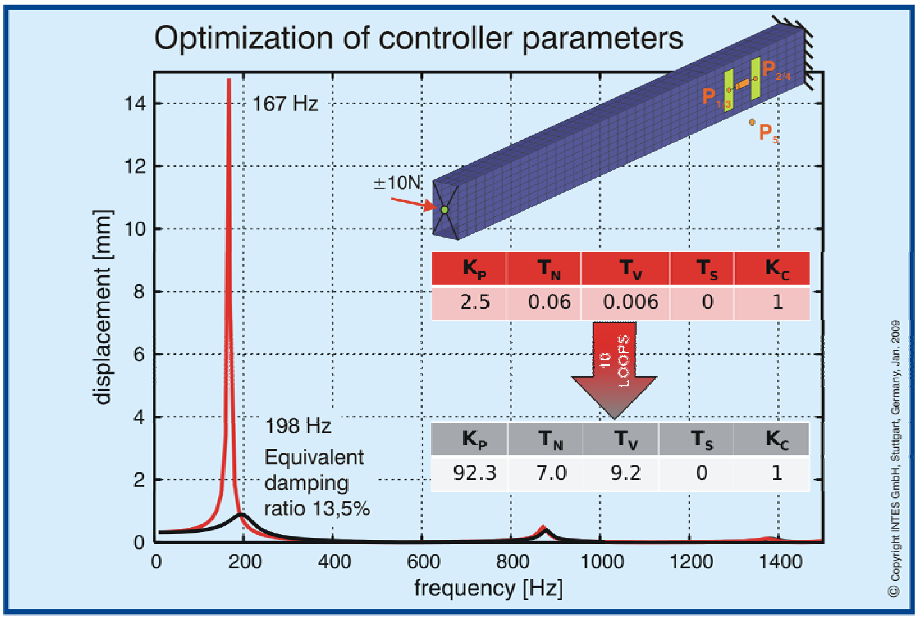


K_P	T_N	T_V	T_S	K_C
2.5	0.06	0.006	0	1

Figure 6: Frequency response and time-history analysis with control element

5: Optimization of Controller Parameters

To detect adequate control parameters would be a hard job, in particular for an analyst who is not very familiar with controller design. Consequently, an optimization is applied to determine the optimum parameter settings.



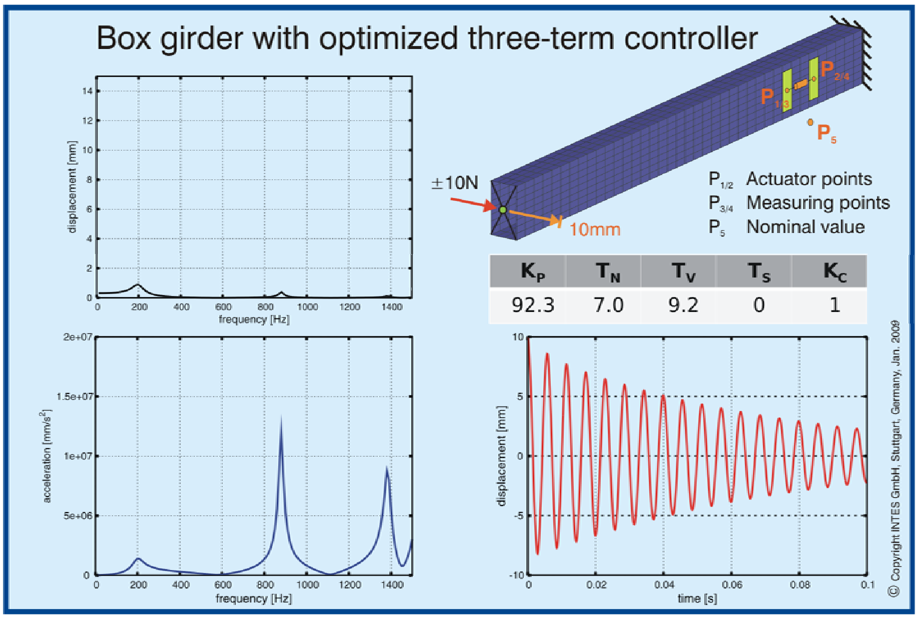
K_P	T_N	T_V	T_S	K_C
2.5	0.06	0.006	0	1

K_P	T_N	T_V	T_S	K_C
92.3	7.0	9.2	0	1

Figure 7: Frequency response optimization of controller parameters

Fig. 7 shows the effect of modified controller settings which are detected by a modal frequency response optimization (see [7,8]) with the displacement amplitude as objective function and the controller parameters K_P, T_N, and T_V as design variables. We see a great effect particularly on the first resonance. The first eigenfrequency moves from 167 Hz to 198 Hz and the equivalent damping ratio for the first mode is about 13.5%. But even modes 4 and 10 get resonances with lower amplitudes.

With the optimized controller the transient behaviour is also much better than before. Now, any disturbance like a forced vibration will be damped out in significantly shorter time than without a controller (see lower left diagrams in Fig. 8 compared and Fig. 6).



K_P	T_N	T_V	T_S	K_C
92.3	7.0	9.2	0	1

Figure 8: **Structural behaviour under optimized controller settings**

Finally, one has to check whether the calculated damping behaviour is technically achievable. To this end, the required forces induced by the actuator have to be checked. The lower left diagram in Fig. 9 gives the relative displacements of the actuator nodes and the force induced by the actuator. Maximum forces have an absolute value of about 10,000 N. This value is rather high, because for many applications an initial displacement of 10 mm is too high. Nevertheless, if the actuator is not able to provide higher forces than a given limit value, one has to do the optimization with a side constraint limiting these forces.

The upper left diagram in Fig. 9 gives the relative displacements of the actuator again and the power needed to damp the vibration. The maximum power value is about 150 mW. The related energy has to be provided by external power sources to achieve the damping behaviour.

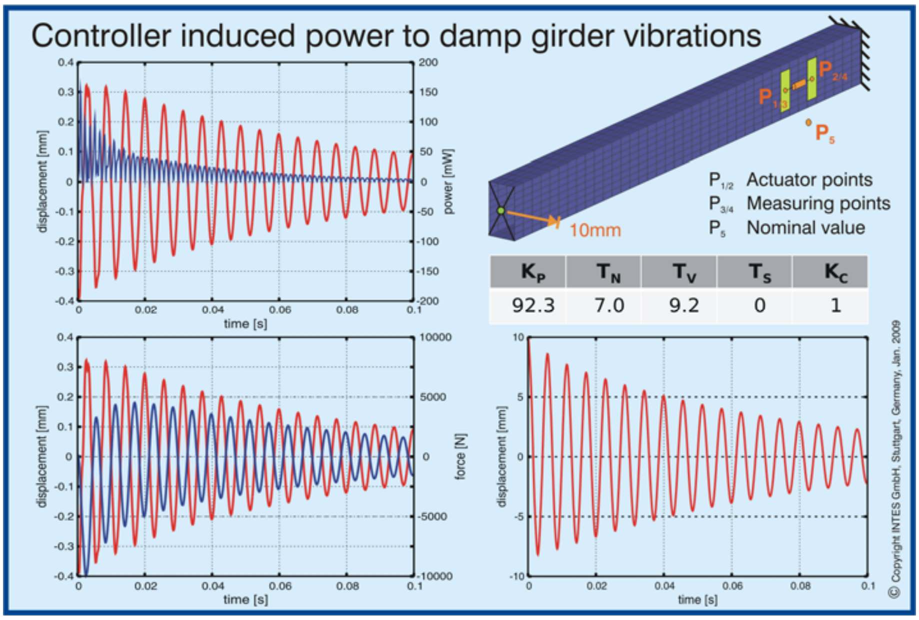


Figure 9: **Power and force required to reduce structural vibrations**

6: Optimum Position of Controller

Beside the optimization of control element parameters it is also of high interest where to locate the controller on the structure. Of course, if you consider a resonance peak like the first mode of the box girder, one would say that the optimum location is as close to the support as possible. But if we take higher modes into account this solution is not such evident. In more complex geometric situations one can find a good position for the controller but probably not the best one. Consequently, another optimization is suggested to solve this problem in an automatic way.

A frequency response optimization is performed with the position of the controller as design variable and the response amplitude as objective function. The starting position for node $P_{2/4}$ was near the girder tip (about 420 mm from the support). After 12 optimization loops a convergent solution for the controller position is achieved. This position is about 46 mm from the support, while we have used a position of about 69 mm from the support for the previous calculations. So, after shape optimization the controller is slightly closer to the support.

It is worth mentioning that this shape optimization does not need to re-mesh the girder or the controller. The incompatible meshing feature which is used to connect the controller patches to the girder mesh is also used to move the controller in every optimization loop. This feature is used in an automatic way during the optimization making the position finding a rather easy task.

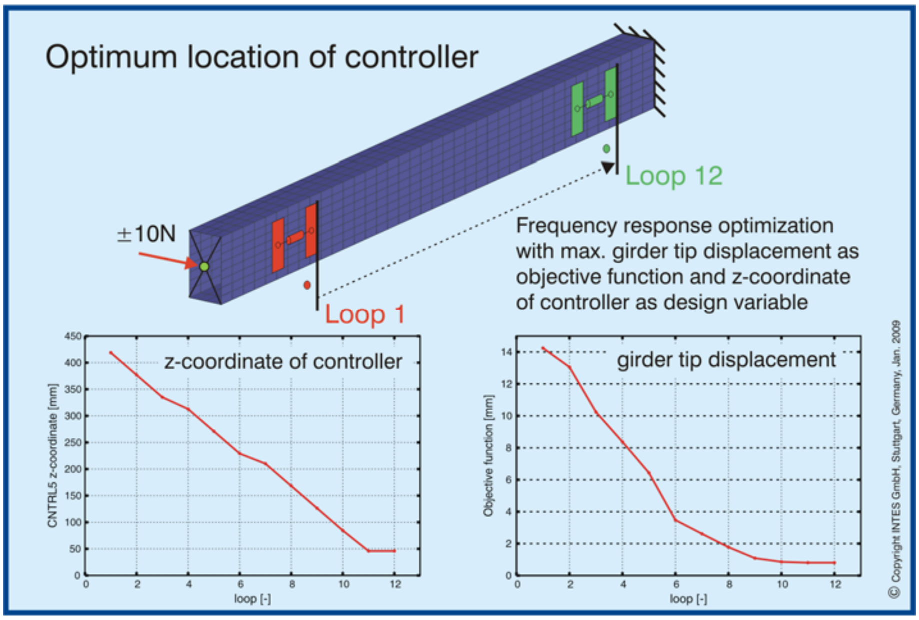


Figure 10: **Frequency response optimization for optimum controller position**

Due to the modified position of the controller, the maximum value for the displacement amplitude during frequency response optimization is about 10% lower at 46 mm than for the previous position at 69 mm. So, there is a potential for improvement by both the controller parameters and the position of the controller. Of course, a combined optimization using sizing and shape parameters is possible and can be used, though in practical application cases a separate optimization of controller parameters and position could be the preferred procedure.

7: Conclusion

Experience with controller design shows the need to integrate the coupled analysis of controlled structures in FE analysis. To achieve this control elements have to be provided in the FE software, where linear control elements have the advantage that all classical methods of linear dynamic calculations can be used like real and complex eigenvalue analysis and response analysis in frequency domain. Time-history response analysis shows the actual transient behaviour of actively controlled structures.

In order to improve the parameter settings of control elements and to optimize the position of controllers sizing and shape optimization can be used with frequency response analysis. In this way, an analyst can make suggestions how to apply control devices to improve the vibration behaviour of structures.

Lightweight CFRP structures are particularly sensitive to disturbances and can highly benefit from active control and the described optimization procedures.

There is no doubt that an integrated FEA software providing control elements and the related optimization features will enable the analyst to strongly support efficiently damped lightweight structures.

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