VIRTUAL REALITY BASED DESIGN AND CALCULATION TOOL FOR IMPROVING DYNAMICS OF MACHINE TOOLS

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This paper presents an extended workflow to improve the dynamic behaviour of machine tools that is fully controlled in the virtual reality environment (VR). The workflow utilizes a common platform for the visualization of results of an experimental modal analysis and the following structural dynamic modification to eliminate the weak points of the design. Based on the overlaid visualization of measured mode shapes, the calculated behaviour and the CAD-model of the machine combined with the parameter modifications in the same virtual reality environment, the VR based approach becomes a development tool that helps to immediately understand cause and effect of complex changes. The advantages of the presented approach are shown by investigating parameter modifications of an I-beam demonstrator and a machine tool.

1 INTRODUCTION

Important criteria for the application of virtual reality (VR) are, inter alia, real-time capability, interaction and the geometrical representation in a 1:1 scale. Due to this advantage in comparison to conventional desktop-visualizations, complex contexts are easy to understand, even by non-specialists [Altintas 2005, Neugebauer 2011a, Kadir 2011].

Mostly, the VR technology is only used in the machine tool industry to visualize design data or measured properties for a following design review. The knowledge gained in this environment, especially regarding the weak points of machine tools, is processed on desktop-applications, which must be handled by experts.

The strict separation of desktop software, Computer Aided Engineering (CAE), and VR is time consuming and potentially leads to loss of information. Using the workflow which is presented in this paper, a method is shown how to overcome the gap between the media by controlling the desktop CAE from the VR environment. Also non-experts of dynamic calculations and measurements are enabled to understand and control the complex procedure improving the dynamic behaviour of a machine tool. The method is realized by a platform which allows the communication between VR, source data and calculation software in real-time, including user interaction.

2 STATE OF THE ART

The experimental modal analysis is a common method to evaluate the dynamic behaviour of machine tools. It is used to detect the causes of vibrations which could appear in poor surface quality on the workpiece, increased tool wear or also acoustic emission. The geometry of the machine tool is meshed by a discrete number of measurement points. After the measurement, the structure is characterized by modal parameters such as eigenfrequencies, modal damping and mode shapes [Ewins 1986]. The latter can be visualized on a wire frame model, representing the movement in a certain eigenfrequency. It is the designer's task to specify the cause and effect of the vibration problems and to submit suitable improvements. The modifications of the structure have to be reviewed regarding their effects on the dynamic behaviour of the structure. In general there are three methods to evaluate the results of the modifications (Figure 1).
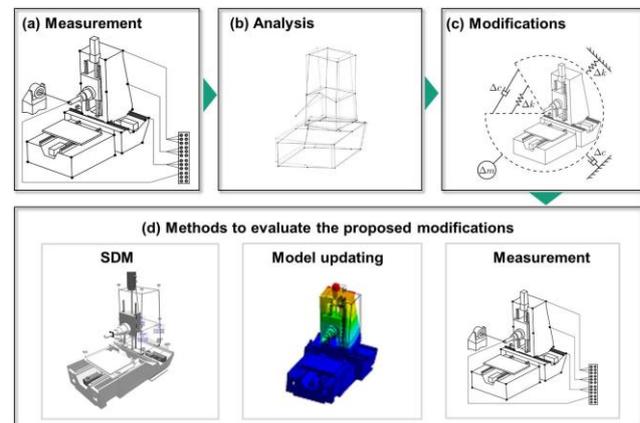
Figure 1. Typical process of evaluation and improvement of the structural behaviour of machine tools

If there are many vibration problems and numerous modifications within the structure, the measurements are usually repeated after changing the structure. Another method is model updating which demands many individual process steps, but results in a precise model on which the modifications could be checked [Jaishi 2005]. Both procedures claim an expenditure of time that is difficult to assess.

The method of structural dynamic modification (SDM) is used in the presented approach. It is an analytical tool which allows quick and simple prediction of the effects of modifications [Avitable 2003]. Because of the rotational degrees of freedom, which are not measured, the results of this method are limited. In many cases estimation is sufficient for an exact result [Avitable 1987]. The method could be divided into the direct and the inverse modification. The first method is characterized by changing the parameters of mass, stiffness and damping to influence the eigenfrequencies. Applying the second method, the user defines the desired frequency. Then calculations will determine which modifications are necessary to achieve the default value.

In the field of machine tools, VR can be used for visualization of simulation data, design review and others [Klocke 2003, Weidlich 2007]. The advantages could be characterized by easy understanding also for non-specialists, enhanced transparency for complex products and inter-divisional communication. By overlaying the wire frame model of the structure with a CAD-model or FEM-model, a comprehensible connection is established between vibrations and assembly units [Neugebauer 2011b]. However, VR is used only for visualization of these applications and software.

The established findings of the design review to improve dynamic behaviour are commonly implemented and checked up with desktop CAE software. This data flow discontinuity is time consuming and potentially leads to loss of information. Moreover, these software applications demand extensive expert know-how.

To extend the possibilities of the VR environment the unidirectional data flow between desktop CAE and VR software has to be replaced by bi-directional data flow. The new workflow applying the VR requires possibilities of interaction enabling users to parameterize the structural modifications. The defined modifications can be checked and reviewed when the model is recalculated directly when working with the VR scene.

3 EXTENDED VR ASSISTED WORKFLOW

The software COVISE (Collaborative Visualization and Simulation Environment) is used for visualization in the VR scene (Figure 2). COVISE supports many known CAD and FEM applications, which allows for easy import of native source data [Neugebauer 2008]. Updated FEM models are used here in order to demonstrate the modification calculations in the VR scene. These FEM models also imply data in the CDB and RST format of ANSYS.
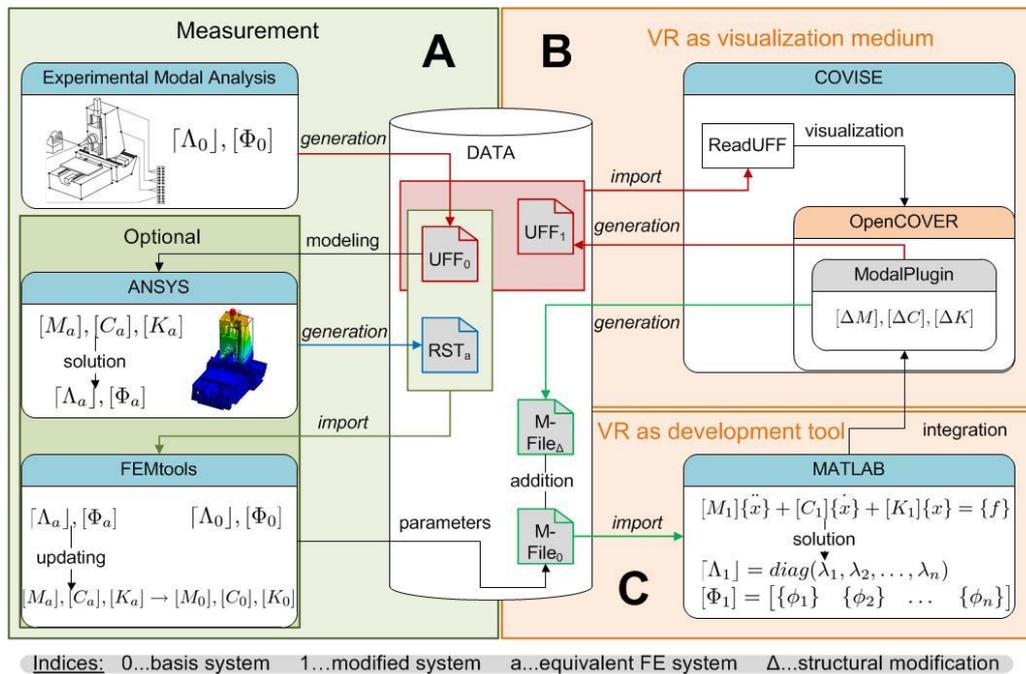
Figure 2. Structure and data formats of the extended VR assisted workflow

The extended VR assisted workflow is basically characterized by the measured modal parameters in the formats of UFF or UNV, which is a standard format in structural dynamic to allow data transfer between several software applications [UC-SDRL 2015] (Figure 2: A). These data packages also contain the coordinates of the measurement points for building a wire frame model.

As a result the mode shapes are visualized as a wire frame model in the VR scene. This visualization could be overlaid by CAD data of the machine or by results of a previous FEM calculation (Figure 3). The wire frame model is editable in the VR scene by the user and visualized in the desired version (Figure 2: B).
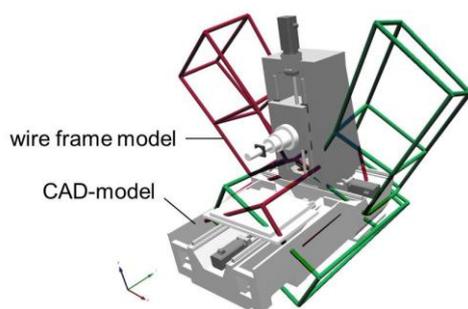
Figure 3. Mode shape of a machine in COVISE overlaid with a CAD-model

COVISE is based on modules that are connected to a network by the COVISE Map Editor. The conclusion for the visualization is formed by the renderer module OpenCover. In addition to this package, the plugin module ReadUFF was programmed to import all existing source data that is used in the VR assisted workflow.

To expand the existing approach the renderer OpenCover was extended by a plugin called ModalanalysePlugin. The modification calculation is controlled by this plugin. The algorithms of the structural dynamic modification are implemented in MATLAB (Figure 2: C). The results of the experimental modal analysis form the database for computing in the UFF format. The basis system data is called UFF0. After the calculation, the results, called UFF1, are automatically imported back into the VR scene. Furthermore all user interactions are controlled by this ModalanlysePlugin. The user can parameterize the modifications by input panels, i.e. defining points and elements of modification in order to start calculations and also to scale and animate the mode shapes.

The combination between the visualization in COVISE and the calculation in MATLAB accounts for many advantages, so basic functionality remains in both software applications. The whole structural dynamic modification in MATLAB is implemented in m-files, so that changes in the algorithms are easily converted and executable without another compilation. MATLAB is particularly suitable for evaluating and editing measurement data, which allows for possible transfer of the method to other investigations in the field of characteristics analysis. Since the

two software applications are linked, the developed concept is also transferable to other VR environments. MATLAB can be started directly from the VR software by using engine functions. The same is possible conversely with so called feedback functions, especially to import the calculated data [Richter 2012].

4 STRUCTURAL DYNAMIC MODIFICATION USING VR

4.1 Direct Modification

After the weak points of a structure have been detected by the experimental modal analysis, it is attempted to influence the dynamic behaviour by design modifications which result from changes of the system properties like mass, stiffness or damping. The modifications are determined by the user, and the effects are calculated for the modified modal parameters. Assuming the linearization of the system, the equation of motion is

$$[\mathbf{M}]\{\ddot{\mathbf{x}}(t)\} + [\mathbf{C}]\{\dot{\mathbf{x}}(t)\} + [\mathbf{K}]\{\mathbf{x}(t)\} = \mathbf{0} \tag{1}$$

In the case of the direct modification, it changes to

$$[\mathbf{M}_0 + \Delta\mathbf{M}]\{\ddot{\mathbf{x}}(t)\} + [\mathbf{C}_0 + \Delta\mathbf{C}]\{\dot{\mathbf{x}}(t)\} + [\mathbf{K}_0 + \Delta\mathbf{K}]\{\mathbf{x}(t)\} = \mathbf{0} \tag{2}$$

The matrices M_0, C_0 and K_0 contain the physical description of the unmodified structure, and the determined modifications are described by the matrices ΔM, ΔC and ΔK. As the matrices M_0, C_0 and K_0 are often not known from the experimental modal analysis, the dynamic behaviour of the system is described by the modal parameters Λ_0 and Ψ_0. Λ_0 is the spectral matrix which contains all eigenfrequencies and Ψ_0 is the modal matrix which includes all eigenvectors. Equation (2) is transformed into the state space form.

$$[\mathbf{A}_0 + \mathbf{A}]\{\dot{\mathbf{y}}\} + [\mathbf{B}_0 + \mathbf{B}]\{\mathbf{y}\} = \mathbf{0} \tag{3}$$

Equation (3) is described in modal coordinates in Equation (4).

$$\left([\mathbf{a}_{g0}] + [\mathbf{\Psi}_0]^T[\Delta\mathbf{A}][\mathbf{\Psi}_0]\right)\{\dot{\mathbf{q}}\} + \left([\mathbf{b}_{g0}] + [\mathbf{\Psi}_0]^T[\Delta\mathbf{B}][\mathbf{\Psi}_0]\right)\{\mathbf{q}\} = \mathbf{0} \tag{4}$$

Where a_{g0} und b_{g0} are defined as

$$[\mathbf{a}_{g0}] = [\mathbf{\Psi}_0]^T[\mathbf{A}_0][\mathbf{\Psi}_0]$$
$$[\mathbf{b}_{g0}] = [\mathbf{\Psi}_0]^T[\mathbf{B}_0][\mathbf{\Psi}_0] \tag{5}$$

Equation (4) is solved as eigenvalue problem with the transformation matrix T.

$$[\mathbf{T}]^T\left([\mathbf{a}_{g0}] + [\mathbf{\Psi}_0]^T[\Delta\mathbf{A}][\mathbf{\Psi}_0]\right)[\mathbf{T}] = [\mathbf{E}] \tag{6}$$

$$[\mathbf{T}]^T\left([\mathbf{b}_{g0}] + [\mathbf{\Psi}_0]^T[\Delta\mathbf{B}][\mathbf{\Psi}_0]\right)[\mathbf{T}] = [\mathbf{\Lambda}_1] \tag{7}$$

Here E is the unit matrix, and Λ_1 is the spectral matrix of the modified system which contains all new eigenvalues. The new eigenvectors are calculated with matrix T.

$$[\mathbf{\Psi}_1] = [\mathbf{\Psi}_0][\mathbf{T}] \tag{8}$$

The dynamic behaviour of the modified system is described by the calculated matrices Λ_1 and Ψ_1.

The modifications regarding mass are basically made at the measurement points. Considering the modifications of stiffness or damping, changes are mainly made between the measurement points. Changes of stiffness can also be made at single points (e.g. spring to ground).
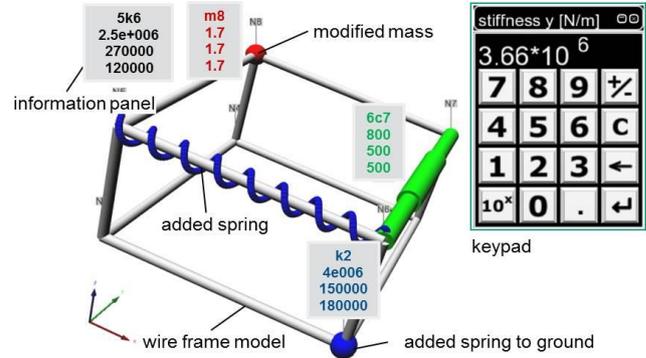
Figure 4. Wire frame model in VR with modified mass and stiffness

The wire frame model of the machine is the basis for selecting visual measurement points in VR. Various modification elements and interaction possibilities are developed within the implemented so called ModalanalysePlugin. Mass, stiffness and damping are epitomized by different simple geometries. The elements are parameterized using an input panel for example a numeric keypad similar to a simple calculator (Figure 4). The parameters of the made modifications are shown by information panels closely positioned to the changed elements in the wire frame model.

4.2 Inverse modification problem

In the case of the inverse modification problem, the desired change of eigenfrequencies is defined and the necessary modifications in mass and/or stiffness are calculated to achieve the required dynamic behaviour. Considering Equation (2), the matrices ΔM and ΔK are computed by determined eigenfrequencies, contained in Λ_1, and by eigenvectors known from the measurements.
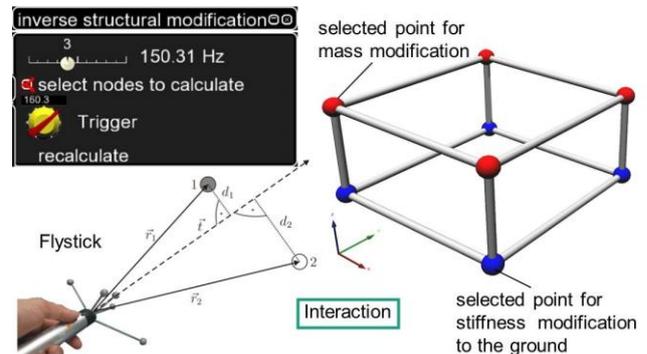
Figure 5. Selection of the modification points and definition of the target

In the beginning, the measurement points are selected where the modifications should take place regarding changes in mass and/or stiffness. Then, the eigenfrequencies, which should be changed, are selected, and the target value of the eigenfrequencies are defined. COVISE supports a lot of tracking

systems and input units. In this example a flystick is used to select and to edit the structural elements and to adjust the desired parameters. All actual settings and configurations are shown by simple panels (Figure 5).

Due to the conditions for the measurements, the modal information is incomplete and the inverse modification problem is not definitely solvable [Avitable 2003, Wahl 1995]. In the case of complex structures, the results contain a great number of mathematically possible solutions. Since many calculated solutions are technically not useful, every modification proposal has to be checked.

5 DEMONSTRATION AND DISCUSSION

5.1 *Direct modification of 3-axis machining centre*

The investigations were carried out based on a 3-axis machining centre (Figure 6). In a first step the dynamic behaviour of the machining centre is described by experimental modal analysis [Richter 2012]. The structure is partitioned into 37 discrete measurement points, and the mechanical excitation occurs in two directions in order to exactly identify the mode shapes. Six mode shapes are located in the range from 0 to 100 Hz.
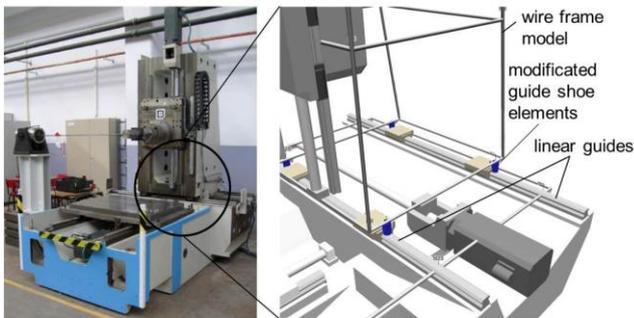
Figure 6. 3-axis-machining centre as wire frame model overlaid with CAD model in the VR scene

A model of the machine is created in parallel using ANSYS, model updating takes place via FEMtools [Neugebauer 2012]. Thus, the new dynamic behaviour, which is afterwards calculated by algorithms of structural dynamic modifications in VR, could be compared with the results of an updated FEM model. After model updating, the difference between the eigenfrequencies of the experimental and the computational modal analysis is on average 0.1 % and the Modal Assurance Criterion (MAC) is at least 87 % [Allemang 2003].

Against this backdrop, a stiffness modification is considered as regards the guide shoes of the linear guides of the travelling column. Between the four pairs of measurement points, the stiffness is changed in each pair in the vertical and the lateral direction.

The structural dynamic modifications are calculated according to the updated FEM-model and the presented workflow in VR. The difference between both methods is on average 1.6 %, the minimal MAC is 89 %. Hence, the quality of the results is comparable with starting values before the calculation, although the rotary degrees of freedom are not measured and the modal information is incomplete. Thus, using the developed VR assisted workflow structural dynamic modification can be realized for components in machining centres, i.e. the linear guide. The advantages of VR-technology in combination with the handling of only one required software platform facilitate more easily the user to understand the dynamical behaviour of a complex structure like a machine tool and also to check the effects of possible changes in real time.

Moreover, it is also essential to implement the calculated modifications into the actual design.

A stiffness change is usually combined with a parameter change of material, design and/or mass, which also influences the dynamic behaviour. One approach might consist in setting the preload of bearings or using other linear guides with other stiffness parameters.

5.2 *Inverse modification of an I-beam*

For the inverse modification, the example of an I-beam is considered to obtain worthwhile results and to avoid the influence and interaction of too many parameters by investigating the behaviour of a complex machine tool.

The results of the experimental modal analysis are used to characterize the dynamic behaviour of the structure. The target is to increase the frequencies of the described example by 10 % by modifying the mass in three measurement points. The result of the calculation for structural dynamic modification is shown in Figure 7. The information carriers display the mass modifications, which are required to achieve the desired frequencies. The calculation results in a total reduction of 0.7 kg, which is partitioned differently between the 3 measurement points.
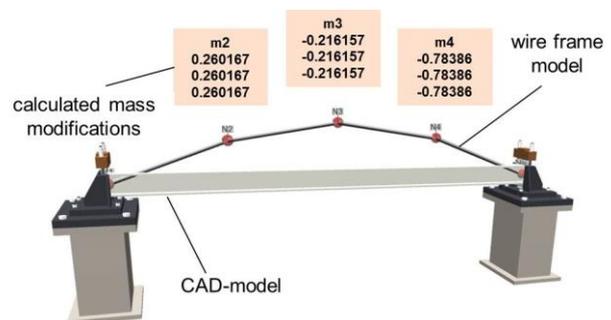
Figure 7. Model of the I-beam in the VR scene with information carriers which display the masses which should be modified

The number of calculated solutions depends on the number of measurement points, modification points and on the modal parameters which should be changed. Thus all solutions have to be checked regarding their technical usefulness. In the case of complex structures, especially machine tools, the inverse modification method is time consuming because of the evaluation of the various results.

6 CONCLUSION

When using the VR assisted workflow to improve the dynamic behaviour of machine tools, the results of experimental modal analysis could be demonstrated in a manner easy to understand even for non-specialists. Based on a previous weak point analysis, the user could check and discuss the proposed modifications to improve the dynamic behaviour directly in the VR environment. This is realized by controlling the algorithms for structural dynamic modification in the VR scene. The software for the visualization and the software for the calculation algorithms are coupled to a common working environment by extending and implementing new modules.

The direct and the inverse modification problems are implemented here. Both these cases were demonstrated by examples. The effects show that the implemented VR assisted workflow leads to exact results which have to be tested for technical usefulness in the case of inverse modification.

When continuing these investigations, it may be possible to display cost information resulting from the proposed modifications, directly in the wire frame model. Furthermore, the interaction possibilities between the user and the VR could be extended by communications by voice or gestures.

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