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Form Error Prediction of Gearcases' Face Milling

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ABSTRACT: Reducing process development time and costs of new parts implies an increasing need of reliable process simulation. In order to guarantee efficiency to machining simulations, Renault has chosen four criteria that must be respected by such numerical methods: Accuracy, Computation time, Robustness and Easy use. A new numerical method adapted for gearcase milling is presented in this paper. This method is based on the modal behaviour of the workpiece and the tool to provide a form error prediction. This paper uses an illustrative gearcase milling operation to present the method. Predicted results and production reality are showing a good agreement.

KEYWORDS: Milling, Vibrations, FEM

1 INTRODUCTION

Machining simulation has started in the early 80's at Renault. First computations were focusing on the effect of clamping forces on form error of machined parts. Then, cutting forces have been taken into account after collaborative work with academics [6]. The goal is to compute the form error of the whole machined surface. A macroscopic point of view is thus adopted to describe the cutting operation.

A static method has been developed in collaboration with ULg then improved as presented in Masset's thesis [4]. Unfortunately, this method is no efficient any more when the workpiece vibrates. It is the case of gearcases face milling.

Macroscopic methods for milling that allow both workpiece and tool to vibrate are already available. For example, the work done by Coffignal *et al.* [3] may be exploited. Such methods are using a geometrical model and a mechanical one. The geometrical model is used to compute the quantity of removed material. The mechanical model is used to compute deflections of both the tool and the workpiece. The geometrical model is updated using the mechanical results. This implies the use of a loop in order to search for the dynamical equilibrium configuration of

the system.

This procedure is time-consuming and, in the case of the simplified methods used at Renault, it is assumed that the cutting force is not affected by the relative displacement of the tool and workpiece neither by the influence of the vibration on the history of the material removal. This implies that no regenerative effects may be taken into account, then chatter prediction has to be treated separately. Methods for chatter prediction are proposed by authors [2].

2 THE OPERATION

The studied operation is the face milling of an aluminium gearcase. The clamping of the part is done using nippers. This clamping design induce no part deformation. Figure 1 shows the finite element model of the part. Arrows are representing the clamping. The machined surface is colored in blue.

The mill follows a complex trajectory around the machined surface. Its diameter is 63 mm, it wears 4 inserts and the rake angle is 90°. The rotation speed is 20 000 RPM, the feed is 256 mm/min and the depth of cut is 1 ± 0.5 mm.

Figure 1: Finite element model of the studied gearcase.

3 OPERATION MODEL

In this study, the mill is assumed to be rigid. In order to take the dynamic behaviour of the workpiece into account, the following equation is used :

$$\underline{\underline{M}} \ddot{\underline{q}}(t) + \underline{\underline{C}} \dot{\underline{q}}(t) + \underline{\underline{K}} \underline{q}(t) = \underline{Q}(t) \quad (1)$$

Where $\underline{\underline{M}}$, $\underline{\underline{C}}$ and $\underline{\underline{K}}$ are respectively the mass, damping and stiffness matrices. Column $\underline{q}(t)$ contains generalized displacements of the finite element model. Column $\underline{Q}(t)$ contains generalized loads, in this case, the cutting forces.

3.1 Integration of equation (1)

Matrices of the equation (1) are big so that the integration of the whole system could be very long. In order to reduce the sizes of the involved matrices, the system is expressed into the dual space of the eigen modes. Calling $\underline{\underline{\Psi}}$ the matrix that contains the whole modal basis of the system, $\underline{q}(t)$ may be projected in the modal space :

$$\underline{q}(t) = \underline{\underline{\Psi}} \underline{y}(t) \quad (2)$$

In order to reduce size of involved matrices and columns, a modal truncature is done. Hats denote truncated modes and indice n denotes kept modes.

$$\underline{q}(t) = \underbrace{\underline{\underline{\Psi}}_n \underline{y}_n(t)}_{\underline{q}_n(t)} + \underbrace{\hat{\underline{\underline{\Psi}}} \hat{\underline{y}}(t)}_{\hat{\underline{q}}(t)} \quad (3)$$

Two more diagonal matrices may be defined here :

$$\underline{\underline{\Psi}}^T \underline{\underline{M}} \underline{\underline{\Psi}} = \underline{\underline{I}} \quad (4)$$

$$\underline{\underline{\Psi}}^T \underline{\underline{K}} \underline{\underline{\Psi}} = \underline{\underline{\Lambda}} \quad (5)$$

Matrix $\underline{\underline{I}}$ is the identity. The following assumption is done on the damping matrix :

$$\underline{\underline{\Psi}}^T \underline{\underline{C}} \underline{\underline{\Psi}} = \underline{\underline{D}} \quad (6)$$

Where matrix $\underline{\underline{D}}$ is diagonal. Combining definitions (4), (5) and (6) with equations (1) and (3) and assuming that truncated modes have only a static contribution to $\underline{q}(t)$, the following system can be written :

$$\begin{cases} \underline{\underline{I}}_n \ddot{\underline{y}}_n(t) + \underline{\underline{D}}_n \dot{\underline{y}}_n(t) + \underline{\underline{\Lambda}}_n \underline{y}_n(t) = \underline{\underline{\Psi}}_n^T \underline{Q}(t) \\ \hat{\underline{q}}(t) = \hat{\underline{\underline{\Psi}}} \hat{\underline{\Lambda}}^{-1} \hat{\underline{\Psi}}^T \underline{Q}(t) \end{cases} \quad (7)$$

In this last expression, one may identify a residual compliance matrix $\hat{\underline{\underline{S}}}$ corresponding to the static compliance of the system contained in the truncated modes.

$$\begin{aligned} \hat{\underline{\underline{S}}} &= \hat{\underline{\underline{\Psi}}} \hat{\underline{\Lambda}}^{-1} \hat{\underline{\Psi}}^T \\ &= \underline{\underline{S}} - \underline{\underline{\Psi}}_n \underline{\underline{\Lambda}}_n^{-1} \underline{\underline{\Psi}}_n^T \end{aligned} \quad (8)$$

Where matrix $\underline{\underline{S}}$ is the compliance matrix of the whole mechanical system. $\hat{\underline{q}}(t)$ becomes the static correction to $\underline{q}_n(t)$. Finally, computed $\underline{q}(t)$ has a good dynamic reliability in the frequency range of the selected modes as well as a good static behaviour.

Integration of equations (7) is done using a Newmark algorithm very quickly since involved matrices are relatively small sized.

3.2 Load modeling

The cutting force is assumed to be *punctual* (applied on the nominal diameter of the mill). This is an hard assumption for two reasons. First, the loading moves along the time so that it is never applied on mesh nodes. This imply over compliance of the finite element model that may have to be corrected as explained in [1] in case of low dynamic contribution.

The second reason is the fact that in reality the loading is more likely a pressure applied on the intersection surface between the cutting insert and the part. Many works focused on fine loading models such as [5].

The cutting force is computed using cutting force laws. These laws are identified experimentally using the protocol described in figure 2.

Figure 2: Cutting force laws identification protocol.

It does not depend on previous computation steps so that no regenerative effects are taken into account.

3.3 Rear insert cutting

Since the mill follows a complex trajectory, no tilt angle is applied to it. This increases risks to have rear inserts to cut the part again (figure 3).

Figure 3: Back cutting.

When back cutting occurs, the corresponding depth of cut is so low that there could be cutting refusal and a high deterioration rate of the cutting insert. Since the chip is very small, it is assumed that the rear cutting applies no loads on the part. Its model simply combines old results and instantaneous surface displacement to know whether the cut exists or not. If

the rear inserts cut, the corresponding material is removed.

4 APPLICATION

4.1 Model reduction

The finite element model used in this case for the gear case contains more than 1 000 000 DOF. A static reduction is used to reduce the size of the stiffness matrix to the 5000 DOF of the machined surface. This static model is enhanced with 27 modes up to 4kHz expressed on the same machined DOF set.

4.2 Test Results

In order to compare computed results to physical parts, 10 gearcases have been machined on a flexible machine tool of the production line in Clon factory, in France. Inserts height have been controlled with a micrometer precision using optical devices. Machined parts have then been measured on a 3D automated measuring device on 70 measurement points.

4.3 Computation Results

At each time step, the whole column $\underline{q}(t)$ is available. It is used to compute the displacement of the force application point that is the only stored data. At the end of the machining computation, all stored displacements are used to compute the form error. Observations of the displacements show that mode 8 is the most excited vibration mode. Its shape is presented in figure 4.

Figure 4: 8th Eigen mode of the clamped part (1373 Hz). Color axis corresponds to displacements in the axis normal to the figure

Figure 5 shows the computed form error and figure 6 presents the form error measured on a representative part extracted from measurements. This result shows good accuracy with measurements on 80% of the surface. This result is showing good agreement with the shape of mode 8 as well. Sectors 1 and 10 are showing poor results that may be due to the fact that the machine tool is not modeled in this computation. More precisely, since mode 8 implies no dynamic compliance in this area, a static effect may be missed due to the lack of machine tool model.

Figure 5: Computed form error result.

Figure 6: Measured form error result. This measure corresponds to a representative part extracted from a 10 parts set.

5 CONCLUSION

The presented method shows good results in this case of gearcase face milling. The model can be extended to the machine in order to take its deflection into account. The whole form error computation is done using matlab. It needs 90 minutes on a laptop with a pentium M 1.7 GHz, 1 Go RAM, which allows us to expect dramatically reduced computation time in the next evolutions.

This method is now used at Renault with strong benefits to predict form errors for new industrials projects.

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