Dedicated Machine Tool Development for Blisk Milling

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For modern jet engines, more and more turbine blade stages are made as one integral part in order to reduce weight.These parts—called Blisks ("Blade integrated disks") or IBRs ("Integrally bladed rotors")—are machined predominantly from Titanium or Nickel-based super alloys (see e.g. [1]). From a machining point of view, they are extremely challenging. The materials used belong to the hardest to cut, the geometries are difficult free-forms and the finished parts are flimsy. Due to the extreme requirements on these parts the machining time and the cost per workpiece are very high today. Despite the challenges of these workpieces, usually standard 5-axis machines are used for machining. With dedicated machine tools the productivity could be increased tremendously. Here the process of machine tool development especially for Blisk milling is presented, using state of the art scientific methods.

Introduction

Blisk machining combines very high requirements in machining dynamics, surface finish and—due to the long cycle times (between 20 and >200 h)—thermal stability. With a machine tool designed for the purpose, the productivity and quality of such a milling process can be improved dramatically. This approach to find the best possible design for this application is described here.

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B. Denkena (ed.), *New Production Technologies in Aerospace Industry*,
Lecture Notes in Production Engineering, DOI: 10.1007/978-3-319-01964-2_6,

Analysis of the Machining Process

This process starts by identifying the desired optimal machining process in a first step. With this knowledge the requirements for the machine can be quantified.

In this first step the most efficient milling strategies are evaluated for typical Blisks. Typical approaches today are e.g. plunge milling, the use of big disk cutters for slotting or the use of ceramic tools with very high cutting speeds for Nickel-based super alloys.

The cutting parameters achievable with the tools today (and anticipated future cutting parameters) are taken as a basis. This information can then be processed in different ways. For the different operations spindles speed, power and cutting forces can be computed. This computation is very straightforward. In general the well-known basic models can be used. The machine dynamics and stability to be able to make fully use of these performance parameters, i.e. to machine productively, must be determined with more effort.

Selection of the Kinematic Concept of the Machine

In general, the most appropriate kinematic build-up for Blisk machining process should be selected. In addition to the usual design criteria like accessibility, ergonomics, floor space, etc. there are characteristics that are not very straightforward to evaluate, especially the machine dynamics for the application to keep finishing times as low as possible and the process stability to be able to us the optimal roughing strategies.

Determination of Machine Dynamics with FEM and Virtual NC Kernel

For this application machine dynamics is evaluated by the actual time that a machine will need to do a typical Blisk finishing operation. This time is determined by many factors.

The kinematic build-up determines how the different axes of the machine must move. Typically the compensation motions of the linear axes to follow the movements of the rotary axes are depending on this build-up. When e.g. a trunnion is turning, two linear axes must move just to keep the same relative position between tool and workpiece.

In addition, this finishing time is of course depending on the axis dynamics parameters. The maximum axis velocity can be determined easily from the mechanical parameters. The achievable acceleration and jerk values when taking into account certain requirements for a dynamic path accuracy and effects like overshoot, cross-talk or in-talk (see e.g. [2, 3, 4]) are more difficult to determine.

With modern simulation programs, such as a "Virtual NC Kernel" [5], very powerful tools are available to determine the effect of both kinematic build-up and axis dynamics on total cycle time. With this different machine concepts can be compared and very accurate machining times can be determined in a very early design stage. It can be computed which parameters (like accelerations) have which effect on cycle time and therefore the ideal configuration can be identified. With this different kinematic concepts and variations can be compared.

This VNCK uses the same inputs as a real control and generates the same outputs. One drawback is that—while axis limitations like filters or max. jerk values can easily be put in—it cannot be determined what values have to be put in because these depend on the mechanical behaviour. Realistic values can be determined from FEM. This approach is shown in Fig. 1.

The mechanical constraints can be anticipated by FEM simulations. Especially important here is the behaviour of the single axis against quasi-static forces (how much will the axis tilt due to acceleration forces, thus determining cross-talk and in-talk) and the Eigen frequencies when excited through the axis drive (these Eigen frequencies limit the bandwidth of the control loop and subsequently limit the achievable gains, filter and jerk settings).

With the results from these FEM simulations (see e.g. Fig. 2) the parameters for VNCK can be determined. With this the operation can be simulated, the time can be determined and limitations preventing shorter times can be simulated.

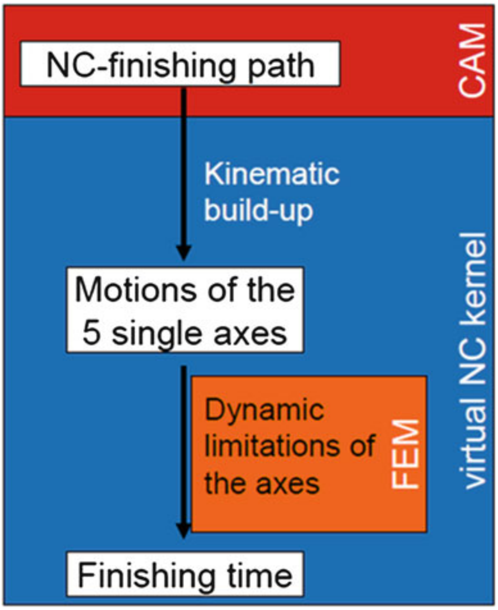

Fig. 1 Simulation approach for determining machine dynamics using VNCK and FEM

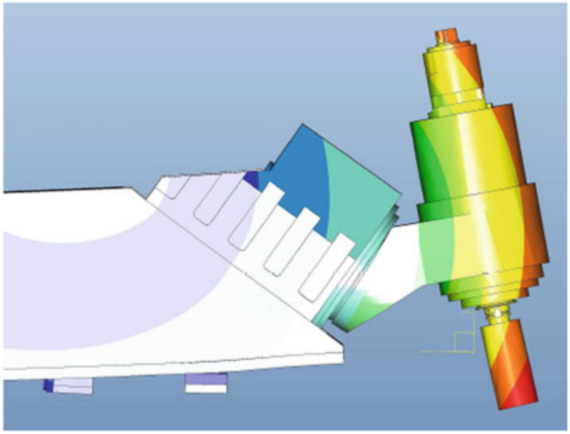

Fig. 2 Example of FEM result: Eigen mode of an assembly

This first result can then be used to overcome limitations, e.g. by changing the kinematic build-up, by systematic mechanical improvements where beneficial, by improving the control optimization.

Determination of Process Stability with FEM and CutPro

The other factor not easy to determine is the process stability of the system. For the Blisk machine development it is crucial that the most efficient strategies and the potential of the tools available today and tomorrow can be used. For this the maximum stable depth of cuts must be determined.

The method of choice today are software packages such as “CutPro”, using the stability lobe theory as described in [6].

While this works excellent for experimental analysis when a certain tool in the spindle is tap tested in order to determine the frequency response function, for a machine to be built this data is of course not yet available. A good alternative is to determine frequency response functions from FEM. To get good results, there is some experience necessary for the assumptions of stiffnesses and damping parameters of single components. With that prior knowledge, very good agreement between simulation and experimental result are possible.

With the results, the most critical frequency can be determined (smallest real part in the FRF). For the corresponding Eigen mode, the critical depth of cut will be proportional to static stiffness and damping ratio. If the Eigen frequency of this mode can be brought up, the critical depth of cut a_{lim} will change approximately with square the change in frequency. So if e.g. by design changes the critical Eigen frequency can be brought up to 120 % of the initial state, a first estimate would be that the critical depth of cut would increase to 144 % from the initial state. This assumes in general unchanged damping behaviour.

Selected Machine Tool Concept

Initial simulations with trunnion concepts following the methods described above showed that with such concepts, there were two constraints limiting the dynamic of the system.

The trunnion axis carrying the second rotary axis, the pallet, the fixture and the workpiece was one limiting factor because of the limited acceleration possible due to the high inertia. The other one were the dynamics of the linear axes because, with a trunnion machine, rather big compensation movements are necessary to follow the trunnion.

So to really come to significantly shorter cycle times, both the rotary axis had to be accelerated and the necessary compensation motion reduced.

The solution was the use of a tilted B-axis as known in machining of single turbine blades as seen in Fig. 3. The total machine concept is shown in Fig. 4.

This concept combines two advantages:

Instead of tilting a trunnion with the very high inertia, the B-axis only has to rotate the main spindle, drastically reducing the inertia. With that, much higher axis accelerations are possible. Due to the stiff build-up with very high Eigen frequencies, also very high jerk limits become possible.

Due to the tilted design, the tool center point (TCP) approximately lies in the geometric B-axis. That means that when rotating the tool the tool center point almost does not move (depending on tool length). Therefore no compensation motions to follow this rotation are necessary.

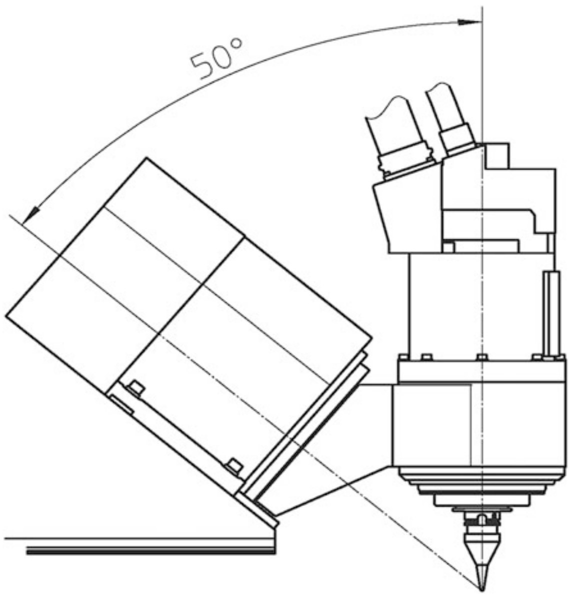

Fig. 3 Side view on spindle and B-axis with a 50° angle in between to allow for tilt motions around the tool center point (TCP)

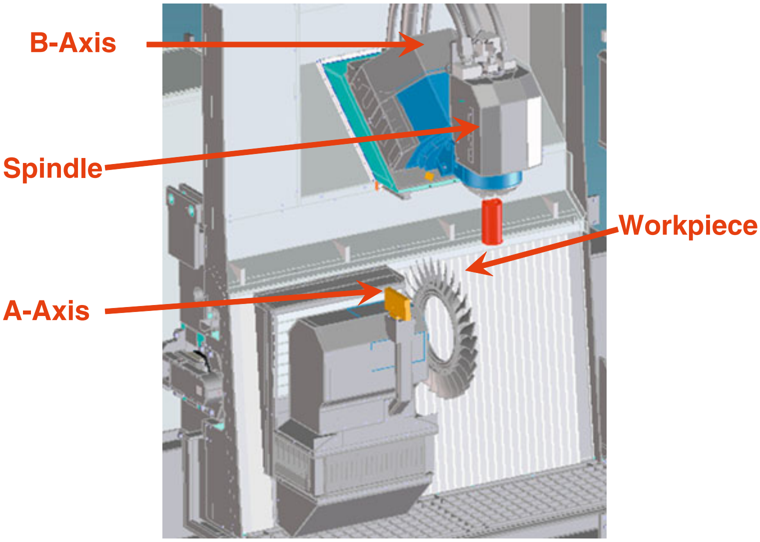

Fig. 4 Machine concept with tilted B-axis

In comparison to trunnions, the simulations have shown that the compensation motions when swivelling are usually reduced by more than 90 % and the time required for such swivelling motions is reduced by about 80 %.

Conclusion

To design a machine, new development tools do exist that allow for very accurate determination of the machine behaviour at a very early design stage. With this methods, it can already be determined if e.g. roughing cuts can be performed as foreseen. Already control parameters can be estimated and cycle times can be anticipated in great details. Bottlenecks limiting the performance can be identified and eliminated. Due to the concentration on such a special application as Blisk milling, breakthroughs in performance can be achieved.

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