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Design and optimization of a machining robot

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Abstract

For manufacturing of large parts made of lightweight materials like aluminum, fiber reinforced plastics or composites for example for the frame in aerospace or automotive industries more and more industrial robots are used. Their main challenge is the low stiffness compared to conventional machine tools resulting in positioning errors. A lot of research is done in order to compensate trajectory errors and enable them for milling operations, which result from the weaknesses in the kinematic. Nevertheless, dynamic properties influence the process stability, which cannot be compensated with the robot control as the dynamic of the joint, and the cycle time of the robot control is limited. Therefore, different robot designs are presented and compared regarding their stiffness, dynamic properties and costs. Afterwards the main weaknesses of the selected design were identified and used for optimization to reduce the deflection and positioning errors during cutting operation. Furthermore, the machine tool structure was topologically optimized for different poses to achieve a higher accuracy in the working space.

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Keywords: industrial robot, machining, topology optimization

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1. Main text

Today, more and more parts are made of fiber-reinforced plastics (FRP) and composites as the weight has one of the most important impact on the energy efficiency of cars, planes or accelerated machine components. Parts made of FRP require machining operations at connecting or functional surfaces and to achieve the final geometry. Mostly

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operations like trimming, drilling and milling are used [1]. These cutting operations have different requirements on the machine tool than metal cutting processes [2]. Compared to metal cutting operations the accuracy required for these operations is much lower. While metal cutting operations require an accuracy of 0.01 mm or even less, the tolerances allowed at parts made of FRP are ten times higher. Today, mostly conventional machine tools, designed for metal cutting operations are used for machining FRP [3]. However, the market of contract manufacturers specialised on FRP machining asks for cheap machine tools with less requirements on the stiffness than conventional machine tools. A survey of manufacturers showed that a stiffness at the tool holder of 2 N/µm and a total trajectory accuracy of 0.1 mm is sufficient. Although the mechanical requirements are lower, no cheap machine tools are available. Thus, the main objective of the research project EFFECTIVE is the development of a new machine tool for machining of FRP, which meets the requirements of the end-user and enables cutting of FRP and aluminum composites with one machine tool.

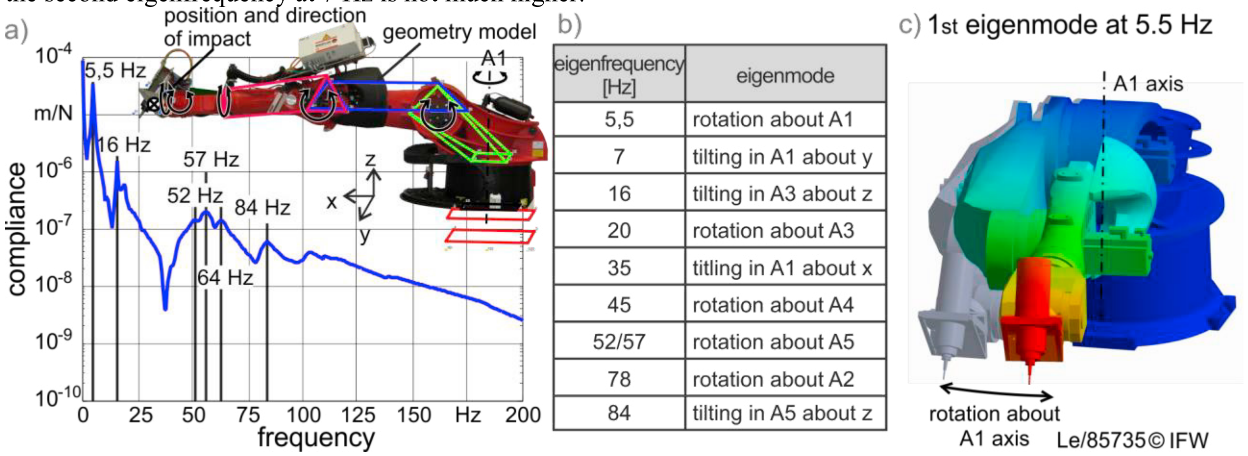
Industrial robots might be an alternative to conventional machine tools for machining of FRP and composites. However, tests show that the positioning accuracy as well as the trajectory accuracy, which includes dynamic effects, need to be improved for the use in cutting operations [4, 5]. Errors occurring on industrial robots can be classified into geometric and non-geometric errors [6]. Geometric errors influence the positioning accuracy by incorrect geometric dependencies between the angular joint position and the tool center point (TCP). These errors can result from the manufacturing process and the assembling due to tolerances in the contact surfaces of the components. The geometry of the link is used for the coordinate transformation, which is generally described with Denavit-Hartenberg (DH) parameters [7]. As errors in the transformation directly lead to wrong joint positions, different approaches for geometric or kinematic calibration are presented in literature [8]. Chen-Gang et al compare different approaches and show the benefit of the additional degrees of freedom for the position and orientation accuracy. As the accuracy values are taken from different publications a reliable comparison cannot be made. However, the pose accuracy could be significantly improved by calibrating the kinematic parameters [9]. The positioning error was reduced to 0.4 mm that is about one fifth of the original error measured for a not calibrated kinematic. As the research on the field of kinematic calibration becomes sophisticated, manufacturers or providers reduce geometric errors in the field. Nevertheless, besides the geometric errors, there are more sources leading to positioning errors of industrial robots. Measurements show that joints have a huge influence on the positioning accuracy. Due to the serial kinematic, high mass and long lever arms, the joints need to apply a high torque for holding and accelerating the links. Thus, most robotic joints are driven by a servo drive combined with a high ratio gear. These gears suffer from a bad torsional compliance and a backlash, which leads to low eigenfrequencies. The state of the art shows that a lot of research on optimizing positioning accuracy by geometric calibration as well as compensation approaches is done.

As a geometric model cannot compensate errors resulting from interactions with the process, many researchers address this issue by developing compensation strategies. The offline programming for backlash and compliance compensation is analyzed by Brüning et al. [10]. They implemented a compensation of process or trajectory-dependent errors in their CAM Software and showed the restrictions concerning the varying process states due to tool and machine wear as well as tolerances in the preformed workpiece. However, the offline compensation requires a well-suited model describing the machining errors and a process simulation for force estimation. Zäh and Rösch developed a compensation of static deflection due to cutting forces by a model-based fuzzy controller. This approach uses a force dynamometer at the workpiece to measure process-forces and an acceleration sensor at the spindle to detect chatter. With this approach Zäh and Rösch reduced the deviation caused by process forces by 70 % [11]. Another approach for online compensation uses a spindle holder with integrated force sensors to measure cutting forces and calculate the resulting deviation. Thus, the drawback of additional sensors required and their setup is cancelled [12].

While actual research projects deal with the optimization of the positioning accuracy during milling operation by the robot control, this paper presents a new robot design. The aim of optimization is the reduction of dynamic impacts as well as static compliance. Therefore, a cooperation with industrial and research partners initiated the research project EFFECTIVE to develop an innovative machine tool for milling of FRP. Their main objective is to design a, compared to conventional machine tools, cost-efficient and more flexible universal machine tool for dry machining of FRP.

2. Weaknesses of industrial robots

Before developing a new machine tool for milling operations, the weaknesses of industrial robots are analyzed to show improvements. These analyses have been done at a conventional industrial robot Kuka KR500-2. For milling operations the robot control KRC 4 was additionally equipped with a Sinumerik 840d control to take advantage of the broad NC functionality known from conventional machine tools. Furthermore, a 20 kW milling spindle is added to the robot endeffector. Cutting tests show deviations, resulting from backlash in the gears and cutting forces, which lead to trajectory errors. The static stiffness of the Kuka KR500-2 varies in a range of 0.5 to 1 N/µm depending on the pose and direction the force is applied. Besides the static deformation, low eigenfrequencies in the machine structure and tool lead to vibrations and thus reduce the depth of cut or limit the cutting velocity and therewith the productivity of a machine tool [13]. As the process stability depends on the dynamic properties, an experimental modal analysis was performed in its weakest position where the robot is completely extended. For experimental modal analysis, an impact hammer is used to excite the robot structure and the resulting vibrations are measured by acceleration sensors. Fig. 1 shows the frequency response function measured at the spindle holder of the robot in y-direction. Dominant eigenfrequencies are identified and the corresponding eigenmode is presented in the table in Fig. 1 b). The eigenmodes are described as a relative movement in the joints. These joints are described with A1 to A6 axis counted from the base to the endeeffector. The first eigenfrequency of the robot is identified at 5.5 Hz. The corresponding eigenmode related to this frequency is shown in Fig. 1 c). It shows that the gearbox in the first axis (A1) is responsible for the low eigenfrequency. This is consistent with measurements on other conventional industrial robots [14, 15] and shows a major problem of the robot kinematic for the use in milling operations. The first eigenfrequency can by increased by optimizing the stiffness in the first drive, only. Nevertheless, the increase in process stability will be very low as the second eigenfrequency at 7 Hz is not much higher.



eigenfrequency [Hz]	eigenmode
5,5	rotation about A1
7	tilting in A1 about y
16	tilting in A3 about z
20	rotation about A3
35	titling in A1 about x
45	rotation about A4
52/57	rotation about A5
78	rotation about A2
84	tilting in A5 about z

Fig. 1. Frequency response function of an industrial robot

The second eigenfrequency results from the bearing of A1 axis and leads to a tilting of the whole robot about the y-axis. This eigenfrequency is not influenced by the drive of the first axis and thus would still limit the process stability when the drive is changed. In this case an online compensation would be necessary to compensate the resulting deviation by the second axis if the resulting deflection is measured or calculated by a dynamic model of the robot. Another solution could be a rotary table bearing with a higher tilting stiffness.

The eigenfrequencies identified during model analysis show that the modes cannot be influenced significantly by the machine structure as they result from the bearings or drives. Only stiff rotary table bearings could increase the eigenfrequency slightly. Still long lever arms lead to high torques acting on the bearing that lead to excitation of oscillations. As the load acting on the joints is changing with the pose of the robot the eigenfrequencies are varying with the angular position of the joints. This is also shown by Vieler et al. who identified the pose dependent variation of the first eigenfrequency in a range of 4.75 Hz to 7.42 Hz [14].

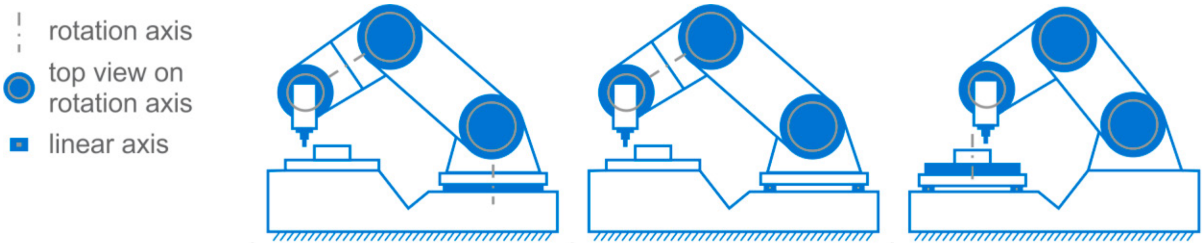
3. New machine concept

Industrial robots might be an economical and flexible alternative for machining applications. However, the experimental results show that static and dynamic properties of industrial robots are not suitable for milling operations. Thus, a new machine concept is invented, which combines the flexibility, large workspace and cost advantage from industrial robots with the stiffness and accuracy known from conventional machine tools. To achieve a high static and dynamic stiffness the new machine kinematic is designed to eliminate the known weaknesses of industrial robots presented in section 2.

3.1. Evaluation of the kinematic for machine concepts

At first different concepts for a machine tool kinematic for machining FRP are developed and evaluated. The first concept bases on a serial kinematic known from industrial robots. As the sixth joint is not required for five-sided machining, it is eliminated. For the second concept a translational axes is used instead of the first rotational axes. It drives the whole robot kinematic, thus increase the working space, and decrease the required length of the links. The third kinematic dispenses two rotational axes of the robotic kinematic by additional axes on the workpiece table. Hence, the kinematic is divided into an actuated workpiece table and a serial robotic kinematic. A ball screw drive and a rotating table actuate the workpiece table for this concept to enable a 5-sided machining. Three rotational axes facilitate the main feed axis and enable the spindle to reach a large working space with different spindle orientations.

The first concept, shown in Fig. 2, is similar to an industrial robot and provides the same structural weaknesses. To achieve a higher stiffness and first eigenfrequency the first axis must be optimized, as it has the main impact on the stiffness.



	1 serial kinematic with rotary axes only	2 linear guided serial kinematic	3 serial kinematic with linear-round table
stiffness	⊖	⊕	⊕⊕
first eigenfrequency	⊖	⊕	⊕⊕
installation space	⊕	⊕	⊖
costs	⊕⊕	⊕	⊖⊖

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Fig. 2 Concepts and evaluation of machine tool kinematics

The static stiffness at the tool interface is calculated with help of the finite-element-method (FEM). The spindle and tool stiffness are neglected as the main approach is the optimization of the kinematic. To identify the impact of the stiffness in the first joint two different round table bearings are analyzed. These bearings are predestinated as they have a high tilting stiffness; they are mainly used for round tables in machine tools. In a FEM simulation an YRT580 is used in the first axis of the industrial robot. To analyze the influence of this bearing on the total stiffness it is replaced by the next larger size YRT650. This bearing has a 45% higher tilting stiffness and about 10% higher radial and axial stiffness compared to the smaller bearing. Still the total stiffness of the kinematic is increased less than 2.6% in the stiffest direction. The same influence can be seen for the first two eigenfrequencies that maximally increase 1.7%. As long as no significantly stiffer bearings are available on the market or a different bearing arrangement of fixed-end and free-end bearings is used the first rotating axis will remain an important vulnerability for the stiffness of this kinematic.

Compared to the first concept, the second concept, shown in Fig. 2, replaces the first rotating axes by a linear axis. This leads to a change in the stiffness at the first joint. As the linear axes drives the robot along the workpiece, the working space of the robot kinematic is increased. This leads to a reduction of the arm-length of the kinematic and thus results in an increased stiffness. A FEM simulation for this concept shows that the stiffness in the weakest direction increases up to 35% even without reducing the arm-length. The first eigenfrequency can be increased 3.5%. Changing the guiding shoes to the next larger model RUE55 with a 29% higher stiffness in horizontal and 9% in vertical direction cannot increase the total stiffness significantly (0.2 to 0.4%). The advantage of the linear axis compared to a rotational axis is the higher stiffness in drive direction and the reduction of tilting.

Dividing the machine kinematic in two actuated parts, the workpiece table and the spindle positioning kinematic has a large effect on the stiffness. This third concept has linear guiding shoes close to the workpiece and thus the process forces are acting on a short lever arm (Fig. 2). This reduces the torque acting on the guide carriage and guiding rail. The reduced load leads to less deviation and tilting and thus a stiff machine kinematic. With the reduced masses and lever arm, the first eigenfrequency can be increased significantly while the amplitude decreases. Due to the rotating workpiece table, the links of the robotic arm can be reduced which increases its stiffness as torques and bending of the structure are reduced. However, as the workpiece table travels on a guiding rail with at least double the length of the workpiece the linear axes and round table need to be enlarged. Consequently, the machine becomes very expensive especially for large workpieces.

Fig. 2 shows the result of the evaluation for the three concepts presented above. They are evaluated according to their stiffness, modal parameters, installation space and cost. As the price is very important for the market of machining FRP and the workpieces have a length of 3 m, the second kinematic is chosen. This concept will be part of further optimization in the next section of this paper.

3.2. Optimization of the static and dynamic stiffness

For metal cutting operations, static and dynamic properties of the machine tool are of major importance. Thus further FEM simulations with help of a more detailed computer aided design (CAD) model are performed to optimize the machine tool. The model bases on the kinematic concept presented in the previous section. The experiences gained from conventional machine tools and the known weaknesses of industrial robots are used to design the CAD model of the new machine tool. Measurements on industrial robots show a strong dependency of mechanical properties to the joint configuration. Thus, the parametric model built up enables the simulation of position dependent static and dynamic parameters. Changing the joint configuration in different design points during simulation allows the analysis of mechanical parameters in different poses. The stiffness parameters of the bearing and drives are adjustable and taken from the datasheet of the bearing manufacturer as measurements show good results with these values. To optimize the machine kinematic the influence of the main spindle is neglected.

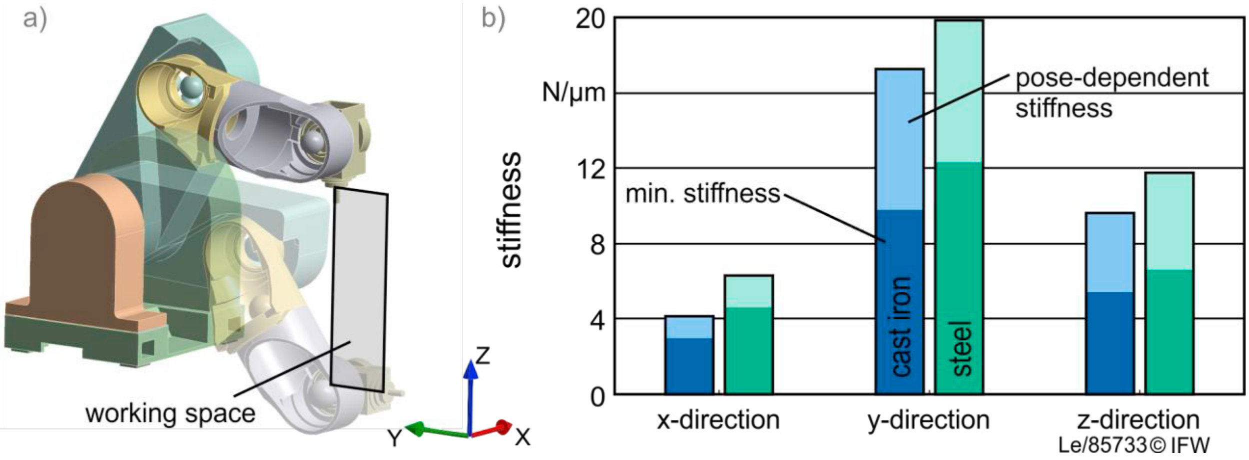

Fig. 3 Pose-dependent stiffness of the robot machine tool for horizontal and vertical milling operation

The simulation using a CAD model before optimization, presented in Fig. 3 a, shows that a stiffness of 3.2 N/µm in x-direction is achieved. This is the weakest direction of the machine tool as the stiffness in the other directions is about 10 N/µm. While the stiffness in x-direction is varying between 3.2 and 4.1 N/µm the changes shown in Fig 3 b) are much higher for the y-direction (9.8 to 17.2 N/µm). Fig. 3 b shows that replacing the cast iron used for the machine structure by steel results in a higher stiffness in all directions. While the modulus of elasticity of the material is increased by 90 % the total stiffness could be increased by at least 45%.

To optimize the machine structure the parts with the most influence on the stiffness are identified. As the links, bearings and drives of industrial robots have a major impact on the total stiffness at the TCP they are separately shown in the pie diagrams in Fig. 4. This detailed analysis allows a specific optimization of bearings for the use in maschining robots. The calculation was performed at a pose for a vertical milling position close to the workpiece table shown in Fig. 4 a). As the x-direction is the most compliant direction, the influences identified for this direction are important for further optimization. Fig. 4 b) shows that the structural components of the machine arm are responsible for 83 % of the deviation. As 17 % of the deviation results from bearing and drive stiffness their influence is low and does not necessarily need an improvement. Optimizing this part can be done by increasing the tilting stiffness, as it is responsible for 75 % of the deviation caused by the bearings and drives. However, the main loss in stiffness is resulting from the base arm (42 %) and arm (19 %). Looking at the other directions shows that the drives and bearings have a higher influence on the compliance of the machine tool.

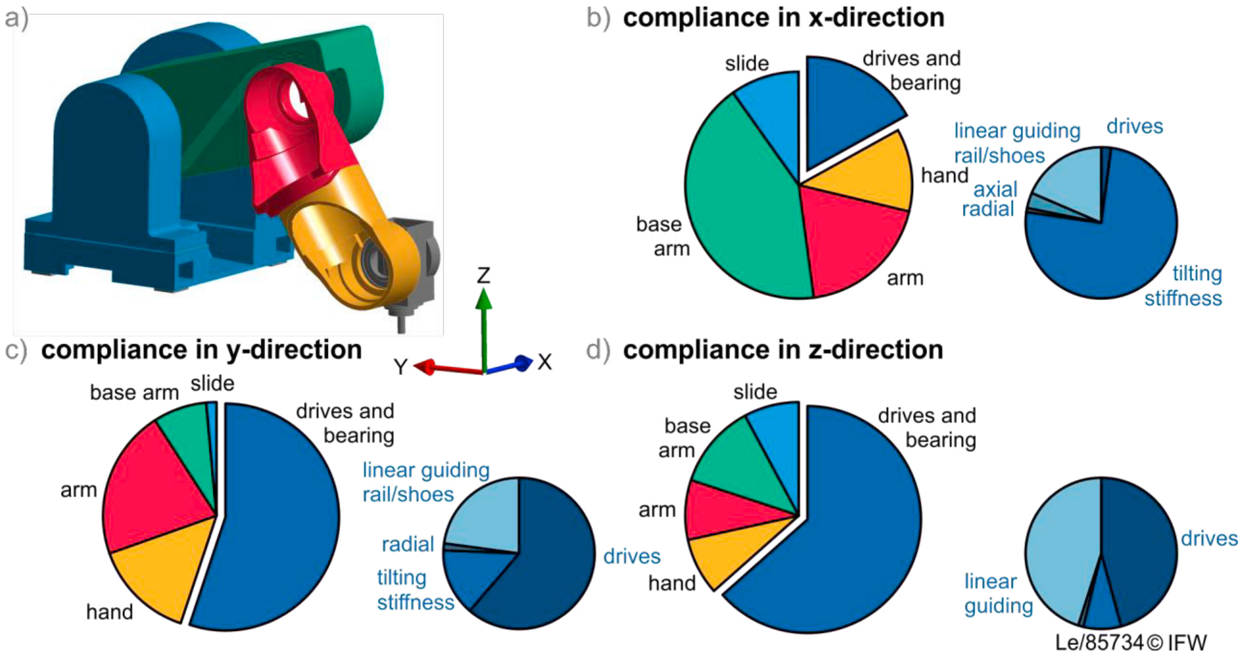

Fig. 4. Impact of the machine tool parts on the stiffness at TCP

Further investigations are currently performed to identify weaknesses in these structural components and optimize them to achieve a higher stiffness. This is done without raising the total mass, as the structure has to be accelerated by the drives. Thus, a topology optimization is performed where the stiffness of the structure is optimized. The optimization of the base arm is shown in Fig. 5. The simulation model shown in Fig. 5 a) is prepared for the simulation by adding additional material to the base arm. Material is added to non-functional surfaces, cavities, holes and edges to increase the stiffness but achieve the functionality of the robot kinematic. Thus, drives, bearings and cable routing are considered. As the stiffness and force flux strongly depend on the position of the robot kinematic the topology optimization is performed in eight different poses, as analyzed before. For each pose, three loading conditions are analyzed where the process forces act in x-, y- and z-direction at the spindle. During topology optimization the strain in the base arm is simulated and areas with the lowest influence on the total stiffness are removed in an iterative process. Fig. 5 b) shows the resulting topologically optimized base arm for three different poses of the robot. The results show that the optimized structure differs for each pose, as the force flux varies. As manufacturing the topologically optimized structures is not cheap and functional, a manual redesign is required. To seal bearings, drives and cables the housing is closed. Thus, the results of the topology optimization are used in the construction of the robot to derive a CAD model with increased stiffness for the whole workingspace. Fig. 5 c) shows the manually derived CAD model. With help of the topology optimization of the base arm the total stiffness in the weakest direction is increased by 25% while the total mass of the base arm is decreased by 5%. As the center of gravity is moved closer to the A1 axis, the required torque for the drive in the first joint can be decreased.

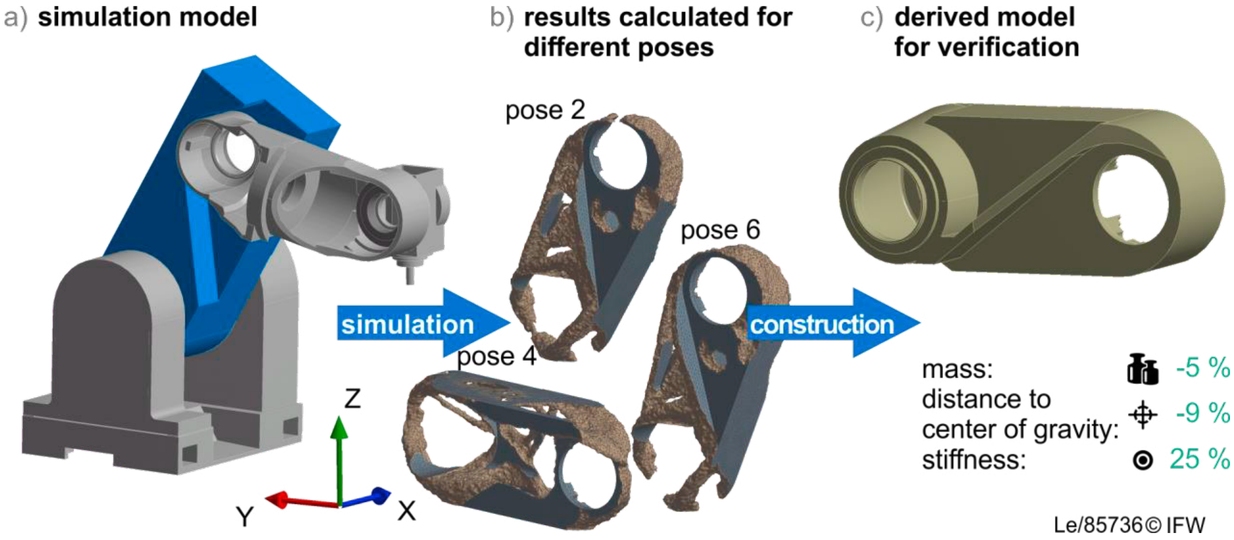

Fig. 5. Topology optimization of the base arm

4. Summary and outlook

Industrial robots might be a cost-efficient alternative to a conventional machine tool if the requirements on the accuracy are lower and a large workingspace is required. Their main disadvantage is the low stiffness, which not only reduces the trajectory accuracy during milling operation, but also reduces the productivity due to chatter. This main drawback is a result of a serial kinematic of industrials robots and can only be eliminated by an adapted kinematic with reduced joints. The lever arm between center of gravity and forces to the bearings must be reduced or the bearing concept changed to significantly increase the tilting stiffness. Three different kinematics are presented and evaluated concerning the capability for cutting operations. The paper shows that a hybrid machine tool combining the best of metal cutting machine tools and industrial robots is a suitable design. Besides the tilting stiffness of the bearing and the stiffness of the drives the structure has an important influence on the static and dynamic properties.

As the main weaknesses of the new machine tool are identified, a topology-optimization will be performed. Due to the pose-dependent stiffness and dynamic properties, the topology-optimization must concern different joint configurations in the working space.

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