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Innovative self-sufficient clamping system for machine tools

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Abstract

In the course of optimizing milling processes, automatic workpiece clamping plays an essential role for a high degree of automation. Hydraulic workpiece clamping offers additional advantages, such as good integrability due to the high power density and the generation of variable clamping forces. The aim of this work is to develop a hydraulic, retrofittable, universal pressure supply for automated clamping fixtures. This clamping system should work without hydraulic and electrical interfaces. An integrated pressure accumulator in the closed system can be charged by the spindle of the machine tool via a separable coupling. This provides hydraulic energy for building up and maintaining the clamping force. Other functions, such as reducing the clamping force and opening or closing the clamping jaws, can be performed either manually by the operator or by actuating the corresponding valves with the machine spindle. The clamping force can be monitored wirelessly via Bluetooth using the integrated pressure sensor.

Keywords: hydraulic clamping, retrofit, automation, closed hydraulic system, interface-free clamping system.

1. INTRODUCTION

When optimizing milling processes, a high degree of automation is usually aimed for, and automatic workpiece clamping plays an important role here [1]. In addition to the good automation capability of the clamping process, hydraulic workpiece clamping offers additional advantages such as good integrability due to the high power density and the generation of variable clamping forces [2]. Apart from enabling automation through hydraulic clamping systems, further general advantages are also expected with manual workpiece clamping. While mechanical clamping fixtures are tightened manually with a suitable tool and defined torque, clamping with hydraulic clamping fixtures can simply take place by switching a valve. This could increase productivity through faster part change processes in order to achieve a high Overall Equipment Effectiveness (OEE) [3, 4, 5]. Another positive effect on the OEE is that quality can be increased through repeatable clamping force, which can also be monitored and documented using integrated pressure sensors [6].

State-of-the-art technology for the pressure supply of hydraulic clamping devices are clamping units integrated in the machine tool. If pallet changing systems are used, appropriate interfaces must be provided for automatic coupling of the hydraulic and, if necessary, electrical connections. Today, many milling machines are equipped with hydraulic clamping units as standard, but retrofitting existing machines is expensive and therefore rarely done.

The aim of this work is to develop a universal pressure supply for hydraulic clamping devices. In order to ensure optimal retrofitting capability and robustness, this clamping system should not require any hydraulic and electrical interfaces. The main focus here is on the question of whether it is possible to drive the pump of the clamping system via the machine spindle using a separable coupling, requiring as little time as possible.

2. CONCEPT AND DESIGN

The basic concept of the clamping system presented here is based on the idea of generating, accumulating and supplying the hydraulic energy directly at the clamping devices in the clamping tower. This enables hydraulic clamping to be carried out directly on the pallet, eliminating the need for an interface to the machine. Each pallet therefore has a self-sufficient clamping unit. All power transmission to the unit is to take place via the machine spindle. This primarily means the drive of the hydraulic pump and also any valve switching operations. This allows the main objective of avoiding hydraulic and electrical interfaces to be achieved. In addition, this design allows the clamping system to be extremely compact and cost-effective, since no additional electric motor is required to drive the pump. The machine spindle drives the hydraulic pump of the clamping system by rotating. A separable coupling is used for this purpose, with one hub acting as a spindle tool that connects to a corresponding hub in the clamping system. The coupling is designed to eliminate the need for precise angular alignment between the machine spindle and the clamping system hub. Even if the machine spindle could, in principle, couple at a defined rotational angle, this approach is avoided because it would increase complexity and error susceptibility. More importantly, it allows for a functionality where the exact position of the clamping system's coupling hub is not always known. It should be possible for the pump to be operated independently of the machine tool, for example, to enable the operator to reload hydraulic energy when changing parts in the pallet station. An additional coupling hub is designed for this purpose, which can be inserted into a cordless screwdriver. After manual operation of the pump by the worker using a cordless screwdriver, the angular position of the coupling hub of the clamping system is undefined. In order to make safe coupling possible for the machine tool, an approach is pursued in which, on the one hand, the highest possible probability is achieved that the coupling parts slide into each other regardless of their angular position and do not collide and block on the end face when they are pushed together axially and, in addition, axial compensation is made possible during coupling so that the coupling parts can move out of the way when they are pushed together. A curved-tooth gear coupling from KTR is selected for this purpose, in which the teeth are sharpened on the end faces, making it less likely that flat end faces will collide. In addition, the sleeve of this special coupling is fixed on the pump-side hub, but can move axially on the hub by 4.5 mm. An O-ring is integrated into the sleeve/hub combination as a resilient element to press the sleeve into its initial position and allow elastic displacement (Figure 2.1). To engage, the spindle must now rotate slowly as it moves axially towards the coupling of the pump. Due to the continuous rotation of the hub on the spindle with the possibility of elastic displacement of the coupling sleeve on the pump-side hub, the coupling parts can slip into each other. The pump-side hub is also rotated from the point of engagement and the spindle can move to the axial end position. As soon as the coupling process is complete, the spindle can drive the pump at maximum pump speed in order to generate the hydraulic power.

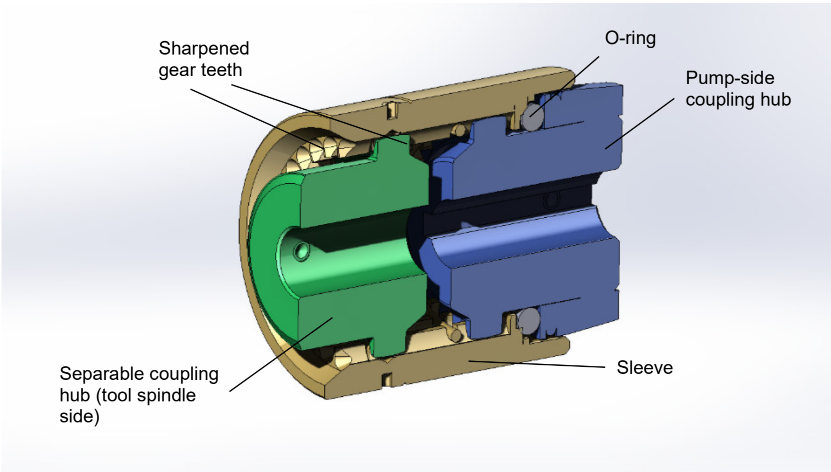

Figure 2.1. Separable coupling

In the unlikely event that the hub does not slide into the sleeve because something is jammed or the teeth actually meet exactly with the end faces and do not slide into each other due to the rotation, the machine has a force monitoring device on the spindle, which prevents a crash by switching off in the latter instance.

A hydraulic accumulator is integrated to enable the clamping jaws to be operated outside the machine during workpiece changes. This accumulator is loaded when the pump is driven by the tool spindle and must be dimensioned so that it is possible to carry out several clamping operations without having to reload in between. This system design (Figure 2.2) with accumulator also makes it possible to maintain the clamping pressure reliably over a long period of time. The accumulator size and preload pressure must be selected so that the maximum clamping pressure to be achieved can be safely maintained over a long period of time, despite internal droplet leakage. In addition, there must be sufficient oil volume in the accumulator to be able to carry out several clamping operations. However, a compromise can be made here in that the full clamping pressure does not have to be reached when clamping the workpiece. When clamping, it is sufficient if the workpiece is held securely in position. The final clamping pressure can then be built up in the machine by the machine spindle before machining begins. On the other hand, the accumulator would have to be disproportionately large. The accumulator design is calculated using the formula for the polytropic change of state of nitrogen with n=1.4 [7]. This results in a calculated available oil volume of 370 ml for the 1 l accumulator with 70 bar gas pre-charge between the maximum pressure of 250 bar and the assumed minimum clamping pressure of 100 bar to be achieved during clamping of the workpiece.

Since the required clamping force can vary greatly depending on the application and component and is often not known precisely [8], but is sometimes simply clamped with the maximum available clamping force, the clamping system is designed so that a standard maximum clamping pressure of 240 bar can be achieved. In order to reliably provide the required maximum clamping pressure over a long period of time, a higher pressure of 250 bar must be maintained in the accumulator. At the same time, however, the maximum pressure limits of the clamping device must not be exceeded, which is why the clamping pressure is regulated by pressure reducing valves. This has the additional advantage that the clamping pressure required for the respective application can be easily adjusted.

The clamping system is also equipped with valves for reducing the clamping force for fine machining. The circuit is designed so that it is possible to switch between high and low clamping pressure without having to build up pressure again via the pump. It is possible to switch from high pressure to low pressure and vice versa. To ensure that this can be done without leakage, a combination of a pressure reducing valve and a pressure relief valve is selected for the low-pressure supply, as shown in Figure 2.2. The switchover is performed by a mechanically operated 4-way, 2 position valve, which can be switched manually or with a movement of the machine spindle (Figure 2.3). The clamping system is designed so that several clamping jaws can generally be operated on the clamping tower. In the application example, there are 4 clamping jaws, each of which is controlled individually via manually operated 3-way, 2-positions valves. This allows the operator to easily clamp and release when changing parts by simply turning the valve switch.

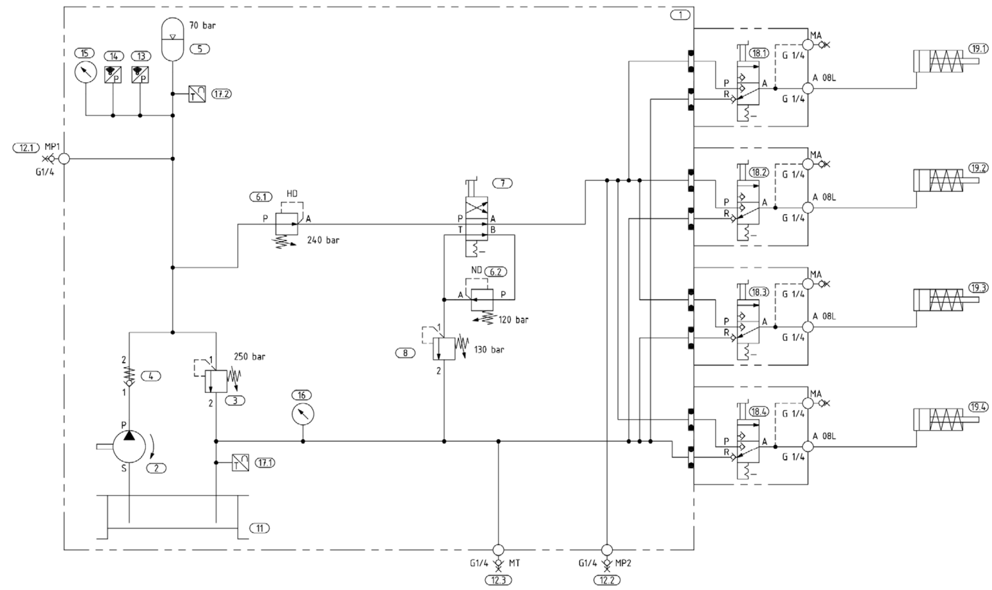

Figure 2.2. Hydraulic circuit diagram of clamping system

Single-acting hydraulic vices with an effective area of 25 cm² are used as clamping jaws. This results in a maximum clamping force of 60 kN at a maximum pressure of 240 bar. The maximum clamping stroke is 4.5 mm, but is additionally limited mechanically to 2 mm in order to prevent the operator's body parts from becoming trapped during clamping as far as possible. This results in a required oil volume of 5 cm^3 per vice, respectively per clamping operation. This means that approximately 74 clamping operations are possible within the limits of 250 bar (fully charged accumulator) and 100 bar (selected lower clamping pressure limit during workpiece insertion).

An external gear pump with a displacement of 2.1 cm^3/rev is selected as the hydraulic pump. At 3000 rpm, this allows a calculated reloading time of 0.2 s, assuming that each of the four vices has been relaxed and clamped once. With the selected pump, speeds of up to 6000 rpm would even be possible, resulting in a calculated reloading time of 0.1 s.

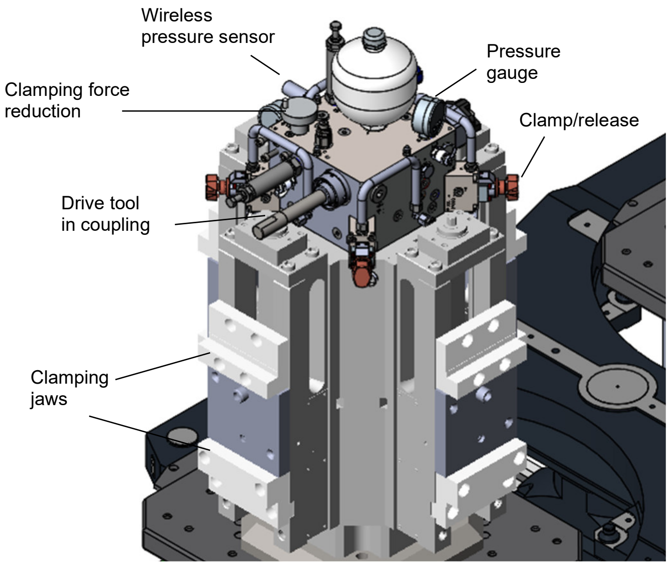

Figure 2.3. Clamping system on pallet tower

The oil tank is flanged to the bottom of the hydraulic manifold and seals hermetically with the manifold. This is necessary to protect the oil from moisture and dirt ingress from chips and cooling lubricant. The tank has a nominal volume of 2.4 l and is filled with 0.8 l of oil. The required exchange volume is 0.6 l. This results in an approximate pressure of 0.73 bar absolute in the tank for an isothermal change of state at maximum oil extraction (accumulator fully charged), which is still acceptable for proper suction by the pump.

Since reliable fixation of the workpiece is relevant to safety, pressure monitoring must be implemented during the machining process [9]. In order to keep complexity low and avoid interfaces, the focus is on wireless pressure monitoring. This also ensures seamless pressure monitoring over a longer period of time in the pallet station. One option for wireless clamping force transmission, as investigated by Denkena, would be to integrate strain gauges on the clamping jaws and transmit the data wirelessly via a CAN master on the pallet to the machine control system via an industrial PC [10]. However, such a solution requires a relatively large amount of electrical energy at the clamping tower. Since no electrical interfaces are desired here, a solution using battery-powered pressure sensors with a wireless interface (Bluetooth) is implemented. Two relatively new wireless sensors available on the market, the PEW-1000 from WIKA and the M5600 from TE Connectivity, are being tested.

A pressure gauge is integrated so that the operator can easily check the available pressure at any time when changing workpieces. In addition, temperature sensors, another pressure gauge on the tank, and additional measuring connections have been provided for validation purposes.

3. RESULTS

When testing the coupling process, it becomes apparent that the strategy of allowing the coupling sleeve to deflect via the O-ring does not work. The stiffness is too high and the resulting travel too low, so that when the front sides of the coupling teeth meet, the machine's sensitively adjusted force monitoring system is triggered. This means that the coupling process must be carried out very slowly. On the other hand, it can be seen that the basic approach of allowing the coupling sleeve to deflect while the spindle rotates toward the coupling is effective. This is more important than the geometrically adapted front faces of the teeth, as these do not completely prevent a collision. It is therefore assumed that the special geometry of the coupling is not necessary if sufficient deflection is provided. With the current design and the cautious coupling process, coupling takes approx. 14 s. A measurement of the accumulator charging process shows that charging from 160 to maximum pressure at 1000 rpm takes approx. 3.5 s (Figure 3.1). This means that the time required for coupling significantly outweighs this and should be improved.

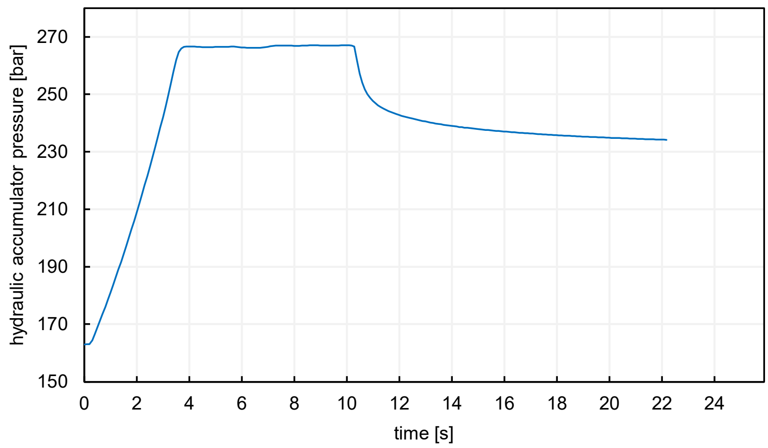

Figure 3.1. Time-controlled charging over 10 s at 1000 rpm

It is also noticeable that the pressure drops rapidly by approx. 30 bar at the end of the charging process. This is attributed to the hysteresis of the pressure relief valve. This effect can probably be avoided if the pressure connection of the pressure relief valve is not connected between the check valve and the accumulator, but between the check valve and the pump. It would also be helpful if the maximum pressure or setting pressure of the relieve valve were not so close to the maximum clampinig pressure. This would also give more reserve capacity in terms of the stored oil volume above the maximum clampinig pressure, which would mean that it might not be necessary to reload after every insertion process. Currently, only 2.3 clamping procedures between 250 bar and 240 bar storage pressure are calculated to be possible. In reality, even a single cycle of release and clamping results in a pressure drop from 240 bar to approx. 225 bar, as all channels are briefly connected to each other when the 3-way, 2-position poppet valve is switched, resulting in additional oil loss to the tank. If the required clamping pressures are more precisely defined, the pre-charge pressure of the accumulator can also be set more advantageously, so that even at higher pressures a better ratio between the amount of oil available and the pressure difference is possible.

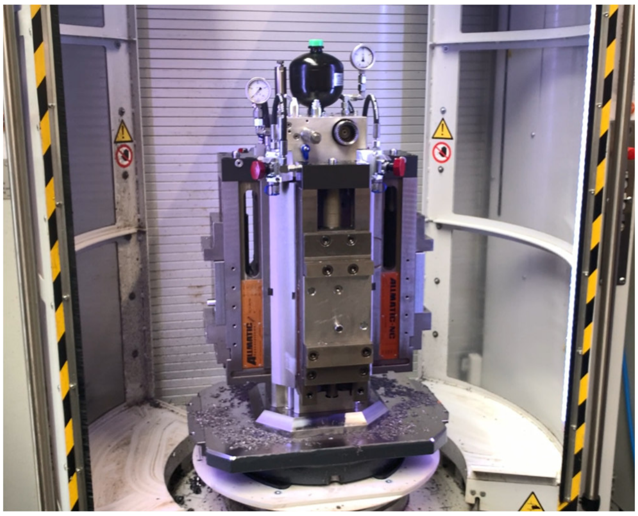

Figure 3.2. Clamping tower with installed clamping system

During validation, the following experiences were recorded with regard to time savings and operational convenience compared to mechanical clamping. In terms of time savings, an improvement of approx. 5 to 10 seconds per workpiece change was observed with a standard 4-sided clamping tower, but this alone does not lead to a profitable amortization period. From an ergonomic point of view, the hydraulic clamping device does lead to an improvement in the process. This effect is sometimes enhanced if the devices are located outside the comfortable working area when changing workpieces, or if the workers are below average in terms of size or strength, which in turn leads to further time savings.

During charging, it can be observed that negative pressure builds up in the tank, but not to the expected extent. When driving the pump, the pressure in the tank quickly drops to approx. 0.85 bar absolute and then does not drop further while the pump continues to fill the accumulator. Therefore, a leak in the tank is suspected. The tank is a welded steel tank that seals radially to the flange via an O-ring on a collar on the manifold, which is the most likely location for a leak. Since the tank is located below the manifold and thus within the clamping tower, and therefore in a fairly protected area, the risk of contamination and moisture entering the hydraulic system is relatively low.

The general suitability of the Bluetooth pressure sensors was demonstrated. Pressure recordings were possible using the manufacturers' application software, and in some cases measurement data could also be exported as CSV files. Measurement and transmission intervals vary and can be parameterized within certain limits. According to the data sheet, the sensors can also communicate with application-specific controllers via standard protocols, but this was not tested.

4. Summary and conclusion

In summary, it can be stated that the principal functionality of the intended concept is in place. There is further potential for optimization, particularly with regard to the drive shaft coupling. This can be improved in terms of design to enable faster engagement of the tool spindle and thus reduce the loading time, which is directly included in the machining time per pallet. Furthermore, the integration of the wireless sensor for clamping pressure monitoring into the machine control system remains to be completed. This would also enable a pressure-controlled loading process, which would optimize the loading time to the necessary duration compared to time-controlled loading. The root cause of the tank leak needs to be identified and rectified. Alternatively, a second accumulator with a very low gas pre-charge could be utilized as a tank. It is recommended that a further optimization be made by switching to hydraulically vented pressure reducing valves. The pressure reducing valves used are atmospherically vented, which poses a general risk of contamination in this operating environment.

5. References

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Biographies

Johannes Gattinger completed his master's degree in mechanical engineering at the Technical University of Munich in 2013 and subsequently earned his doctorate there in 2018 at the Chair of Medical Technology. Since then, he has been working as a project leader and technical product owner in the field of hydraulic systems and manifolds at Weber-Hydraulik GmbH in Wörth an der Isar.