

Interaction between the machine tool and its foundation

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Abstract

The article deals with the interaction between the machine tool and its foundation. The main problem here is the possible factual uncertainty of this interaction, especially if the machine is placed a different way than in a statically certain way. Uncertainty is meant here, in particular, the ignorance of the actually transmitted forces between the machine and its foundation, and their change in time either by the machine (effects of its own operation) or foundation (transmission of vibrations from the surrounding, or consolidation of the subsoil). The present solution of this state is to directly measure these transmitted forces between the machine and its foundation, which can be performed during machine installation and the alignment of its internal geometry or during its real operation. This solution, together with other necessary prerequisites, should to create a generalizable procedure for unambiguous and repeatable alignment of the machine geometry during its installation, to record undesirable vibrations transmitted from the surrounding to the machine, or to capture the excessive vibration of the machine. This solution will allow to design more efficiently the fundamant or subsoil, and in the case of the development of machine prototypes, the knowledge gained will, for example, make it possible to optimize the number of machine leveling elements and their positioning.

Keywords: machine tool; foundation; leveling element; alignment geometry; load cell

1. Introduction

The article deals with an interaction between the machine tool and its base. For certain types of machines, their foundations are an integral part of their frames. This interaction affects different processes, respectively machine properties, such as the course and success of alignment of the machine's internal geometry during its alignment, the geometrical stability of the frame over time, the machine's static stiffness, or even its dynamic compliance.

The reason for the research in this area is, in particular, the effort to increase the utility properties of the machines by means of this correct interaction between the machine and its foundation. These utility properties of machines are those properties that this interaction directly or indirectly affects. In particular, it is unambiguous and thus repeatable alignment of the machine internal geometry during its laying on the base, as well as the possibility of targeted influence on the static stiffness of the machine, or its dynamic compliance, up to the fact that knowledge of the processes taking place on the machine-base interface, allows to design more efficient fundamentals of the machine, respectively necessary subsoil preparation under this foundation.

The main problem in the most commonly used method of installing and aligning machine tools on a foundation is the ignorance of the actual transmitted forces between the machine and its foundation. This is especially true in the case of a statically indeterminate state when the machine is placed on more than three points. The direct consequence of this ignorance is, for example, the uncertainty and thus the unrepeatability of the unambiguous alignment of the machine geometry by setting it on its foundation. This leveling process depends in particular on the experience of the executing workers. Other con-

sequences of ignorance of the actually transmitted forces over the machine leveling feet are, for example, that without them it is not possible to properly design the necessary foundation structure including subsoil, nor to check back the used leveling elements, or to optimize their number and location.

2. Literature research

Specialized literature, for example, articles [1] to [9], deals with the alignment of machine tools.

First of all, the notion of alignment means that the machine tool is based on the base so that its internal geometry (tool or workpiece movements) is close to the ideal by adjusting the machine on its base by leveling feet.

All posts agree that this is one of the most important work in the machine installation.

In the case of precision or ultra-precise machining, this is a fundamental process [2], [4], or in the case of large machine tools [3], where the frame (with relative elastic bed) is subject to a change in internal geometry due to the workpiece (variability of its weight and the center of gravity position) [2], or due to the transfer of machine's moving structures [7], or respectively due to changes in the foundation or subsoil (e.g. by consolidation).

The authors of all articles also agree that inadequate alignment of the machine basically leads to a loss of its geometrical accuracy, and furthermore, its possible reduced lifetime, resp. premature wear of some moving parts [4].

Aligning the machine tool on a basis can be a one-off matter where the angular deviation of the reference horizontal surfaces (e.g. machine axis guide surfaces) is monitored, and the machine alignment is performed using commonly available leveling wedges. This type of

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balancing is overwhelmingly based on the experience of the executing workers, and the most commonly used gauge is bubble or digital spirit level [4]. The reason for leveling in this case is in particular the imperfection of the base surface, or inaccuracies in the manufacture of abutment surfaces for the feet on the machine bed, as well as the geometric inaccuracy of the surfaces for linear guideway machine axis. In the case of very precise machining, or in the case of particularly large machines with long travels and / or long travels. In the case of very precise machining, or in the case of large machines with long travels, or machines with high workpiece weight variability, the alignment process can take place more often (in principle it can be continuous), mostly in an automated process [1], [3]. The machine feet will then be formed by their own stroke actuators and, in addition to the above, the reason for the leveling may also be the deformation (elastic compression) of the leveling feet or the fundament itself due to a change in load (influence of the weight of the workpiece or the shifting part of the frame), or change of fundament geometry due to temperature change, or settlement of subsoil. Information about angular deformations is obtained, for example, from digital spirit level [1], [3], by measuring the current difference of a horizontal axis servomotor while moving in both directions [4], by refraction of light in a liquid [8], by the principle of connected vessels [1], [6], or through the fundamental law of the horizontal liquid level [6]. The alignment of internal machine geometry is closely related to the optimization of the number and positioning of the leveling elements [9].

Literature [9] to [18] deals with leveling feet of machine tools, or their connection with flexible and damping elements.

[10], [12] and [14] divide the feet into two most common types, the bolts (screws) and the wedges, see Fig. 1. The basic design is design without flexible and damping elements.

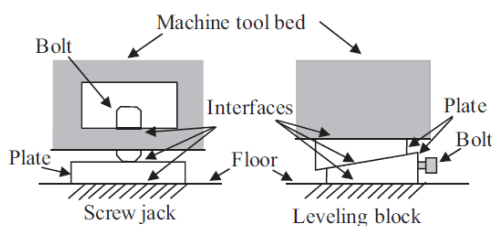


Fig. 1. Leveling bolt (on the left), leveling wedge (on the right) (taken over a modified from [12])

The division into screw and wedge footings also results from the long-standing, and basically, consistent practice of machine tool manufacturers, as well as from the world's leading manufacturers of these leveling elements such as Dynemec Systems, Isoloc, Farrat, Nivell, Unisorb, Airlac Schrepfer and others.

Virtually all manufacturers offer both of these types of feet, either only in the basic version or in the design with certain flexible and / or damping elements. According to [10] or [11], these are mostly rubber or plastic pads,

glued, vulcanized or loosely laid on the bottom or top contact surface of the shoe. However, it is also possible to use, for example, steel coil springs, possibly in combination with the abovementioned damping materials.

By leveling bolt is meant a threaded foot with usually a fine pitch to achieve a larger ratio and for smaller actuating forces. Leveling bolts are used for lighter machine tools, with less leveling accuracy requirements, cheaper, smaller installation dimensions, and in the simplest form they are easy to manufacture by self-help. They are often equipped with an inner spherical surface allowing balancing the perpendicularity of the foundation and the leveling foot axis (normally $\pm 3^\circ$).

The leveling wedge is used for more precise alignment of machine tools, can carry more load, has greater rigidity and a large internal ratio thru the wedge system. In principle, it is a set of wedges, which alters the leveling change. Typically these are non-self-locking wedges with a 20° apex angle. Wedge feet are used loosely laid or anchored. Technically, the anchorage in the drilled hole is basically solved either by gluing the threaded rod to the chemical mortar, or by using an expansible anchor with conical elements.

In general, it is recommended (especially wedges [14]) on the below surfaces add special materials to increase the actual contact area of the feet & foundation (and thus to increase the stiffness), or the feet are provided with vulcanized rubber on the lower surface.

Both types of leveling feet can be anchored to the foundation or used as a loose one. The anchoring generally brings advantages in increasing the contact and, therefore, the overall stiffness of the foot, in keeping with its unambiguous position, positively influencing the modal (but also static) properties of the machine, allowing the bed to be tightened (to draw it closer to the foundation) while balancing the internal machine geometry, etc. On the other hand, it is accompanied by certain disadvantages, such as more expensive machine installation, the risk of damaging the waterproofing of the foundation, or the collision of the anchor bolt (or drill) with the base reinforcement, requirement the minimum depth of the foundation, the more difficult to install additional damping elements, etc.



Fig. 2. Leveling bolt

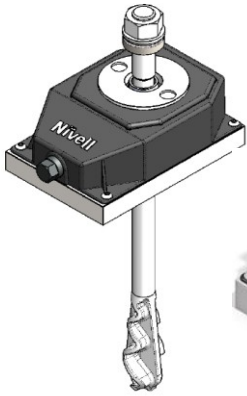


Fig. 3. Leveling wedge - anchored type (taken over a modified from [19])

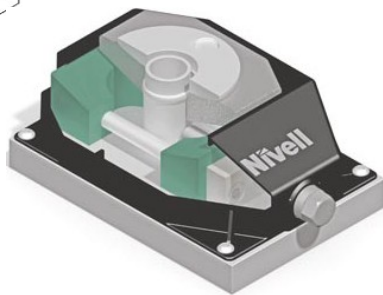


Fig. 4. Leveling wedge - view inside (taken over a modified from [19])

2. Summary of introduction

In summary, the leveling process of the machine tool on its base is extremely important, resp. the alignment of its internal geometry is conditional on the appropriate mounting of the machine on its base. This means in practice, in particular, the optimal number and positioning and alignment of the positioning elements, their suitable type, and the necessary composition of the foundation itself, including adequate ground preparation. And since the base of the machine affects its supporting structure, it should be taken into account when designing the frame.

As already mentioned, in the case of a statically indeterminate interaction between the machine and its foundation, they are not commonly known the real transmitted forces in the individual leveling elements. And the ignorance of these actually transmitted forces in relation to the current state of the machine or its surroundings is a fundamental limit in the proposal, respectively in the implementation of a correct placing the machine on the foundation. Another disadvantage of the current process of aligning the machine's internal geometry is that it depends on the experience of the executing workers.

3. Dividing machines according to the used footings, the necessary foundation and method of alignment of the inner geometry

If we ignore machines with an absolutely self-supporting compact skeleton placed on three leveling feet, and also very large machines (with the characteristic axis starting at 5000mm to tens of meters), we will limit our frame's interaction with the foundation and the leveling method of alignment their internal geometry to 3 general machine groups.

I. Machines relatively light and simple, with a relatively rigid skeleton, without the need for a special foundation. Typically, this group will include a three-axis vertical centre with C-frame, with a weight of up to 6 tons, which is loosely laid on the foundation without special requirements on it, on commonly 6 bolt feet.

A foundation without special requirements is meant a foundation or ground floor that meets the normal requirements for flooring production areas. Under certain conditions, these machines can also be installed on floors of production buildings.

In the case of machines in this group, only the leveling of the work table is typically performed with respect to the horizontal level. The leveling is usually done by means of a spirit level placed in the middle of the table and its leveling is monitored against the horizontal plane. If the table is moving, then the symmetry of this vertical alignment with the center of stroke of the respective axis is also monitored. The leveling itself is done by adjusting the outer leveling feet (floor projection), and after reaching the prescribed leveling, the inner feet are tightened so that they do not break this level. They only compensate for the deflection of the bed caused by the weight itself or weight of the whole frame.

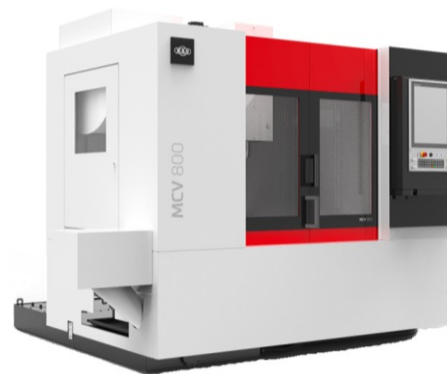


Fig. 5. MCV 800, three-axis vertical centre with C-frame 4tons, 6 leveling bolts

II. Machines heavy, more sophisticated, requiring a separate foundation, especially because of their weight, with a relatively rigid frame.

In this group, for example, there will be a five-axis center with a top gantry with a biaxial swivel cradle, weighing up to 20 tons, freely laid on a separate base. If required for increased machine accuracy, geometric stability or increased dynamics, the machine can be anchored to the foundation. The leveling wedges will predominantly be used as leveling elements.

A separate machine base of this group is required mainly due to their relatively high weight and the normal flooring of the production areas does not have sufficient load carrying capacity. In the case of a requirement for increased accuracy or dynamics of the machine, this basis is separated from its surroundings, in terms of vibration transmission, respectively is isolated.

Process of alignment internal geometry of machines in this group are essentially identical to those of Group I, with the difference that wedge feet are used as leveling elements. Due to the principle of these locating elements (their stick - slip effect, hysteresis), the machine is always adjusted "from bottom to top", so the leveling feet are initially adjusted to their lowest possible height and the leveling is done by increasing their installation height.



Fig. 6. MCU 700-5X, five-axis centre with top gantry
18tons, 6 leveling wedges

III. Machines bigger than in Group II, respectively a machine with a flexible skeleton, requiring a separate foundation that forms an integral part of the machine frame, and significantly affects its overall behavior.

This group will include, for example, a large five-axis vertical center with a cradle table diameter of more than 1000mm, or, for example, a multifunctional turning center with a turning length of over 3000mm. The machine is always anchored to its foundation and leveling wedges are used exclusively as leveling elements.

The foundations of these machines are always separate, vibration insulated from its surroundings (island base). The design of the foundation for this group of machines should be done in collaboration with the structural engineer, and after a previous geological survey of the subsoil. Separateness of the foundation is required not only because of the high weight of these machines, but mainly because these machines, respectively frames of these machines are not designed as self-supporting. Due to their ground plan dimensions, they are elastic, with a large number of leveling feet, and thanks to anchoring, the foundation is an integral part of their frames.

Leveling the internal geometry of these machines is done by adjusting the leveling wedge, again in a "bottom-up" manner. At the machine tool builder, at the beginning of the mounting process, the bed (or the frame base part), is aligned so that the surfaces for the linear guideway of the horizontal machine axes reach the prescribed vertical alignment over their entire length. Usually, during the assembly, this leveling is checked as the weight of the further mounted machine parts acts. When installing the machine at the customer, the internal geometry of the machine is aligned again with the adjustment of the leveling wedges. In this case, the leveling of the tool or workpiece movement relative to the horizontal or vertical plane is checked and adjusted, again within the entire

stroke of the respective machine axes. One can talk about straightening the motion of machine axes and their vertical alignment. In the case of adjusting this group of machines, the direction and magnitude of the forces to which the individual feet are subjected is unknown, and some of the feet may also be pulled out of the base in order to obtain a satisfactory internal geometry.



Fig. 7. MTC 630, five-axis multifunction lathe centre
up to 37tons, up to 35leveling wedges

4. Case study

This case study deals mainly with Group I. and II.

The sensitivity of the machine to its correct adjustment on foundation can be demonstrated by relatively simple numerical calculations. These show the influence of machine alignment on its static and dynamic properties. Calculations were made for a small vertical center with C-frame (MCV 800) and a medium-sized five-axis vertical center with a top gantry (MCU 700-5X). Both machines are placed on 6 feet, the MCV 800 uses the leveling bolts, the five-axis MCU 700-5X uses the leveling wedges.

The first of the calculations shows the change in the value of the first natural frequency of the machine, resp. the shape of this frequency, in the absence of one of the feet. This state simulates the case where the foundation of the machine results in some of the feet being much less loaded than the adjacent feet.

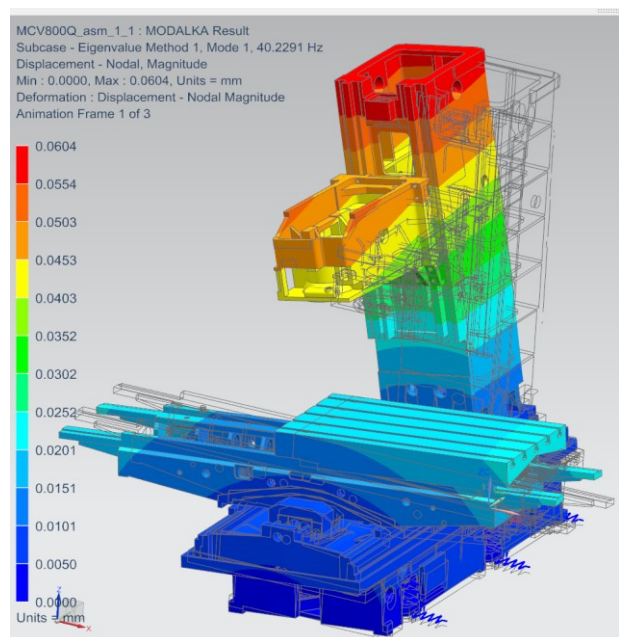


Fig. 8. Modal analyses of frame MCV 800 on 6 feet

Fig. 8 shows the first eigen frequency of the MCV 800 machine frame in the standard way of placing on all 6 feet (FEM implementation using a vertically flexible ball joint with a vertical stiffness of $500\text{N}/\mu\text{m}$).

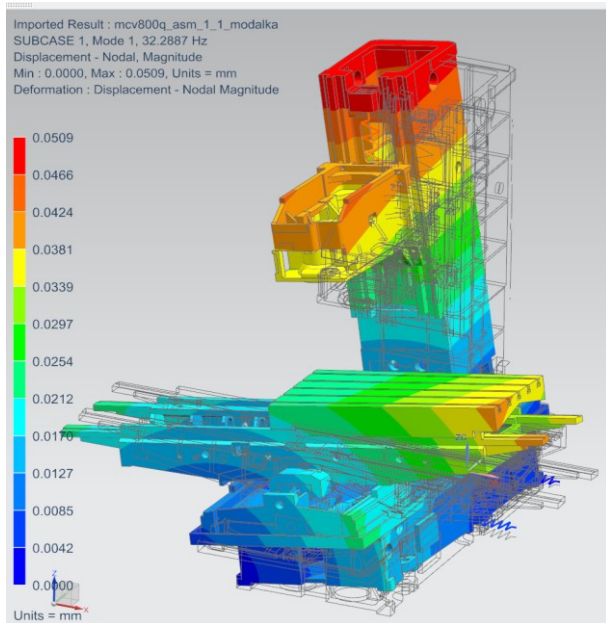


Fig. 9. Modal analyses of frame MCV 800 on 5 feet

Fig. 9 shows the result of the simulation in the absence of one of the feet - here the right front foot (essentially randomly selected). In this case, the decrease in the value of the first eigen frequency is to 80% of the value if the placing is performed in a standard manner. The mode shape related to this frequency changes, part of the bed, the sledge and the table are added to the movement. The machine foundation is considered to be perfectly rigid and flat.

In the case of the MCU 700-5X, the vertical stiffness of $3000\text{N}/\mu\text{m}$ was given to the feet and the decrease of the first natural frequency for the loose machine is at 88% of the value for the standard placed machine.

These numerical calculations show the degree of sensitivity of frame's behavior to the result of the alignment process. The first eigen frequency decreases (to 80% and 88% of the original values, respectively) illustrate the non-negligible degree of interconnection of the whole system "machine - leveling element - foundation (- subsoil)". And then with different ways of aligning the machine (i.e. basically with different preload of individual feet) can create conditions for different frames behavior in both dynamic and static areas.

As already mentioned, by changing the placing or alignment process (or by removing a particular foot here), the static state of the frame or its inner geometry can be modified. Inner geometry is the relative geometric position between the tool and the workpiece. Of course, this can be observed throughout the machine's working space (volumetry), but the following calculations are limited to one characteristic point in the machine's working space (in the center of the machine axis

strokes). The load was gravitational acceleration, the restrain conditions were identical to the previous modal analysis. From the essence of FEM calculations with gravity, the deformation of the skeleton deposited on 6 feet was always first calculated and the skeleton with the absent foot was then calculated. The difference between these two states can be seen as an undesirable impact of improper adjustment of the foot.

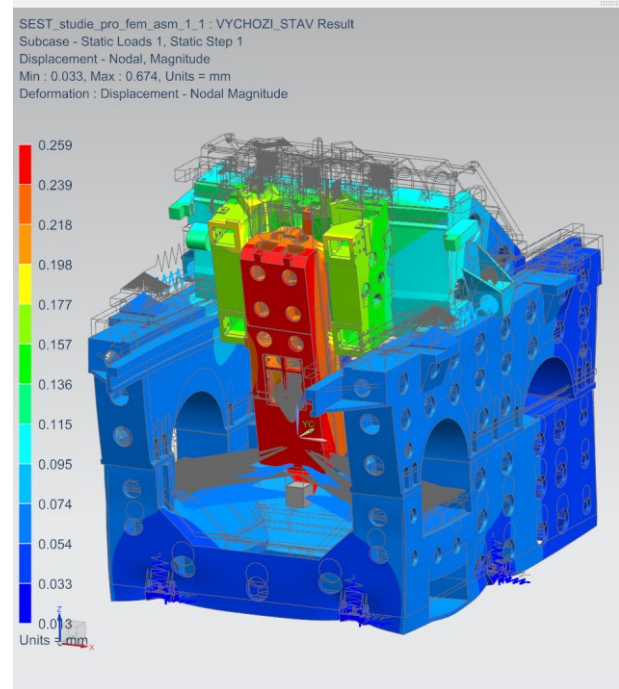


Fig. 10. Static analyses of frame MCU 700-5X - standard way of placing

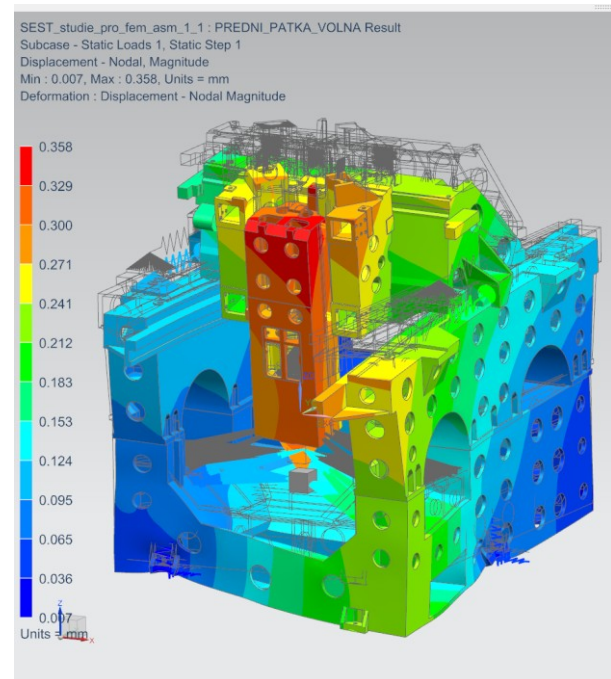


Fig. 11. Static analyses of frame MCU 700-5X - placing with absence one of the feet

Fig. 10 shows the change of position tool and workpiece of the MCU 700 under the Earth's gravity load. The calculation is made for standard placing on all 6 feet. This change of position of both points (in the weightless state these points are coincident) is the initial state of the given structure (the gravity acceleration still present). Fig. 11 shows the change of position of the above points when removing a particular foot (here again the right front foot). The difference of these feeds and feeds by default (in initial state) determines the change of tool and workpiece position in the absence of this given foot. In this case, this relative position change is 0.033mm. In the identical case of the MCV 800, this relative change in tool and workpiece position is 0.08mm.

Problems of static uncertainty of machine mounting on more than three feet and thus the necessity to measure certain quantities for obtaining further input data for possible solution of this issue, is also evidenced by the expected discrepancy between reality and the calculation of forces acting between the machine feet and its foundation.

Fig. 12 shows these forces in the MCU 700. Of course, the numerical model again contained the entire deformable frame, in the figure only the bed of the machine is shown. Other boundary conditions are the same as in the previous calculation.

The results of the calculations for both of the above machines show the greatest forces in the middle feet, which is also expected, since the center of gravity of the machine skeleton is located closest to just these feet. However, the reality of setting up the machine is such that the machines on the six feet are always aligned on the outer four feet (floor projection) when the level of the work table is reached, respectively the machine as a whole, and only the bed deflection along the longest axis is compensated with the middle feet. This results from imperfect self-supporting of the bed, resp. frame of the machine. It is known from the practice of aligning these machines that these middle feet carry only a minor part of the weight of the machine.

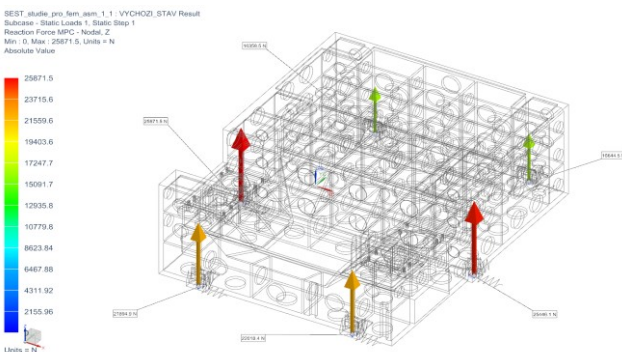


Fig. 12. MCU 700-5X - reaction forces of the foundation

5. The proposed solution

The solution to the above problems would be to know the immediately transmitted forces between the machine feet and the foundation. In particular, knowing these forces during machine alignment based on the machine, and preferably even during the machine's own work, would in particular allow the machine to be set up uniquely and repetitively, avoiding excessive or negligible load on some of the feet. Monitoring of these forces even during the machine operation would also register a possible change in the distribution of these forces between individual constituent elements due to, for example, subsoil consolidation. Another benefit would be to detect any excessive machine vibration or to pick up undesirable vibrations from the environment, not permissible for machine operation. Furthermore, by measuring these forces, a possible systematic overloading of the machine could be detected, in some cases a machine crash in the sense of collision of moving parts, or, for example, partially compensated for the workpiece weight. In the case of knowledge of the actual transmitted forces between the machine and its foundation within the construction of the machine prototype, this information would allow to design a suitable foundation for this machine, including the necessary condition of the subsoil. Another use of this knowledge would be a more correct optimization of the number and positioning of the leveling feet.

To measure the actually transmitted forces over the machine feet, a measuring apparatus has been designed and implemented (and partially tested) - see Fig.13.

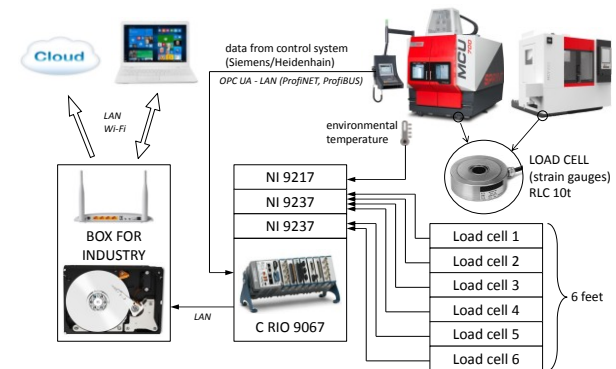


Fig. 13. General measurement scheme

Load cell is the RLC 10t type from the Czech company M.E.N. Expert, who is an authorized supplier of strain gauge sensors to the leading US Vishay Precision Group. It is an industrial, closed (IP68) stainless steel load cell equipped with four strain gauges connected to a full bridge. The load capacity of the sensor is 10t with a safe overload of 150%, which is quite sufficient for the intended experiments. The bandwidth of the sensor in the dynamic area is not known, but it can be assumed that it will be tens of Hz. It is unlikely that shorter periods would be needed in the research.

Compact Rio platform, from National Instruments, was chosen for data acquisition. Measuring cards were used

NI 9237. The card is fast enough not to limit measurements in the dynamic area.

For certain experiments it will be necessary to synchronize the measured forces with the data from the machine control system, namely the actual position of the machine axes (i.e. the center of gravity of the whole machine), the actual acceleration of the axes (which will generate additional forces to the feet), etc. via the Profibus or via the OPC UA interface.

In the Fig.14 - 16 are designed and implemented foot assemblies including load sensors for both the bolt and wedge feet.

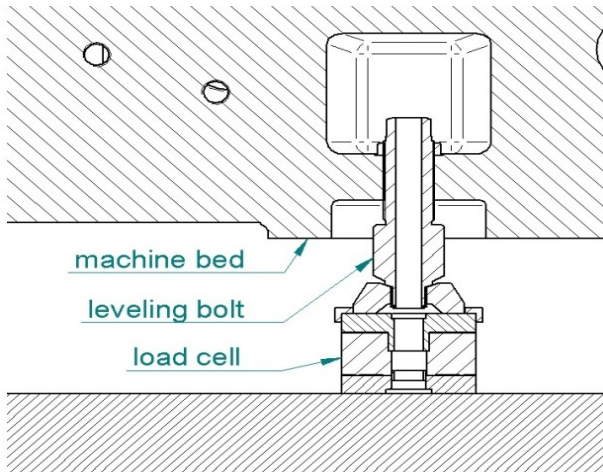


Fig. 14. Leveling bolt with load cell

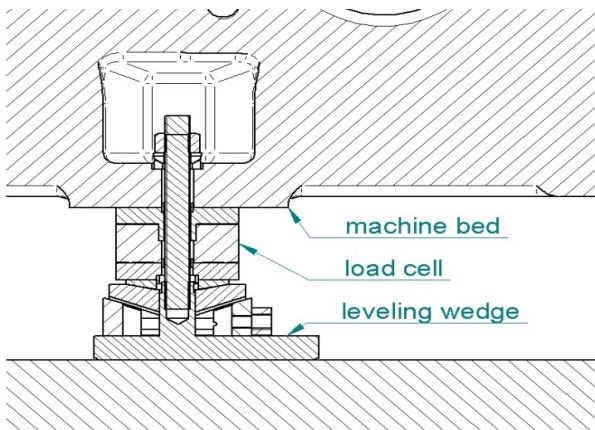


Fig. 15. Leveling wedge with load cell



Fig. 16. Leveling bolts with load cells on the machine

At present (1Q, 2019), the Rio device is put into operation and the first experiments are performed. For example, the travel of machine axes (moving machine's center of gravity) on the course of the measured force is tested, and the bandwidth of the load cells against dynamic events at the speed jump will be tested. Looking for the optimal writing of measured forces and its necessary sampling. The load cells were calibration and verification before the first use of this.

6. Conclusion

The proposed solution for direct measurement of the forces transmitted by the individual leveling elements will ensure their controlled load. Furthermore, this solution will help to clarify the relationship between the distribution of transmitted forces by leveling elements (respectively changing them over time) and changing the internal geometry of the machine. This knowledge will make it possible to propose a unique and repeatable procedure for alignment the machine's internal geometry during installation. More generally, the proposed solution will lead to an increase in the quality of the machine tool placing on its fundament due to the knowledge of the interrelationship between a certain level of placing and the technical-economic characteristics of the machine. Other specific effects of the proposed solution will be, for example, gaining information on the need for a possible re-alignment of the machine geometry (e.g. for consolidation of the subsoil, or geometric changes in the fundamentals), or information about the occurrence of excessive or inadmissible vibration of the machine (its possible failure) or its surroundings. By knowledge of the actual transmitted forces thru the leveling elements, it is also possible to verify the current predictive methods regarding the optimization of the number and location of these elements on the machine.

7. Literature

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