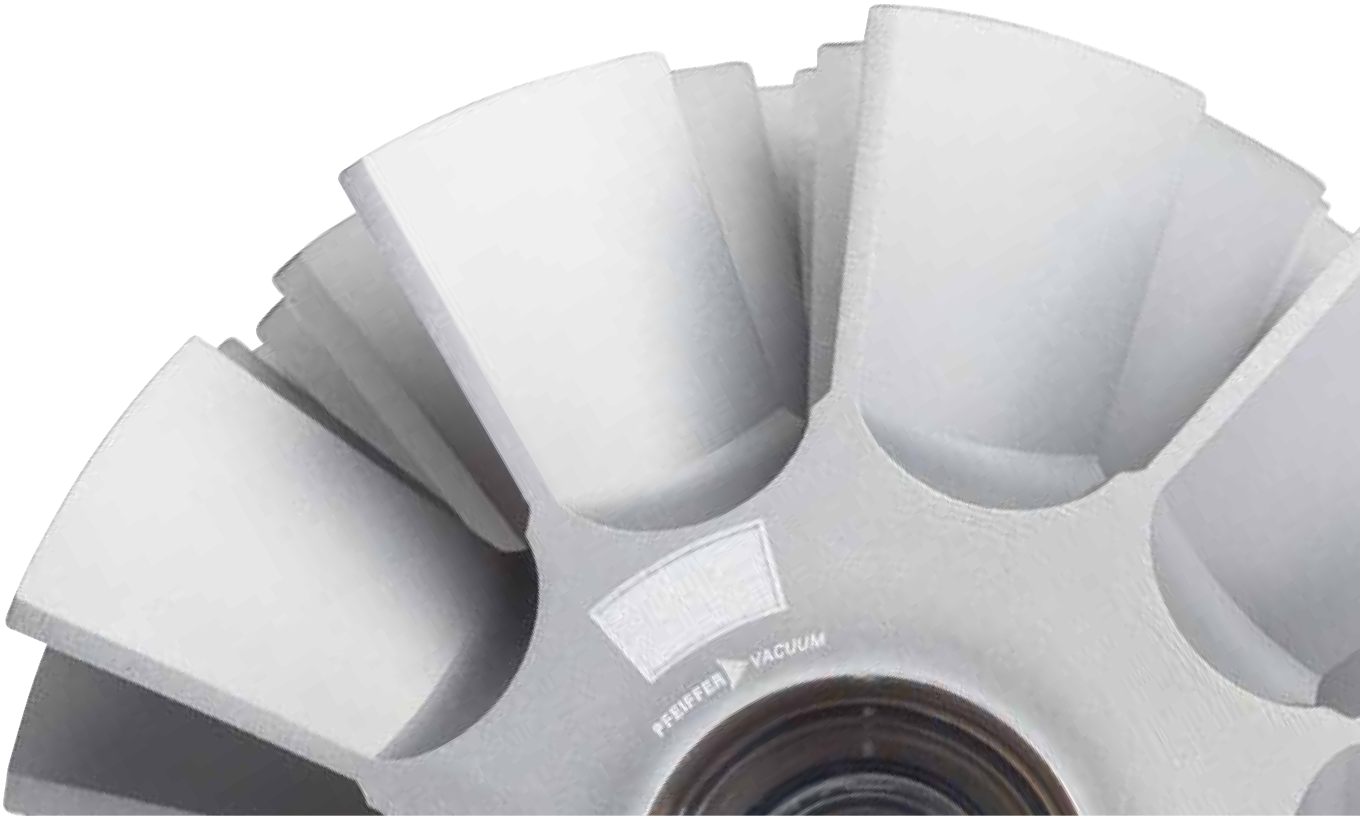
Revolution in Balancing Technology:

Laser Balancing™ Makes the Operation of Turbopumps Even More Efficient

Since its invention in 1958, the turbomolecular pump (turbopump for short) has been regarded as the driving force behind high-vacuum technology. Thanks to its reliable vacuum generation, it has become indispensable in the semiconductor production industry and among others.



PFEIFFER VACUUM

Its inventor, Willi Becker, who at that time had been the head of the technical laboratory at Arthur Pfeiffer Vakuumtechnik GmbH (today Pfeiffer Vacuum GmbH) for 13 years, could hardly have dreamed back then that 63 years later, a laser beam would be responsible for further revolutioning the turbopump. This is because laser balancing is the latest and most efficient method of balancing technology that increases the service life and performance of turbopumps. Laser Balancing was developed and patented at Pfeiffer Vacuum - the company where Willi Becker invented the turbopump back in the day.

Structure of the turbopump

To this day, the turbopump remains essential for generating oil-free high and ultra-high vacuum. Immediately after its invention, it gradually replaced existing pumping principles for vacuum generation. In the 1960s, the demand for high vacuum began to increase more and more, quickly establishing the turbopump as the standard for high and ultra-high vacuum generation in a wide variety of applications. Without its use, many process steps in semiconductor manufacturing or coating would not be possible.

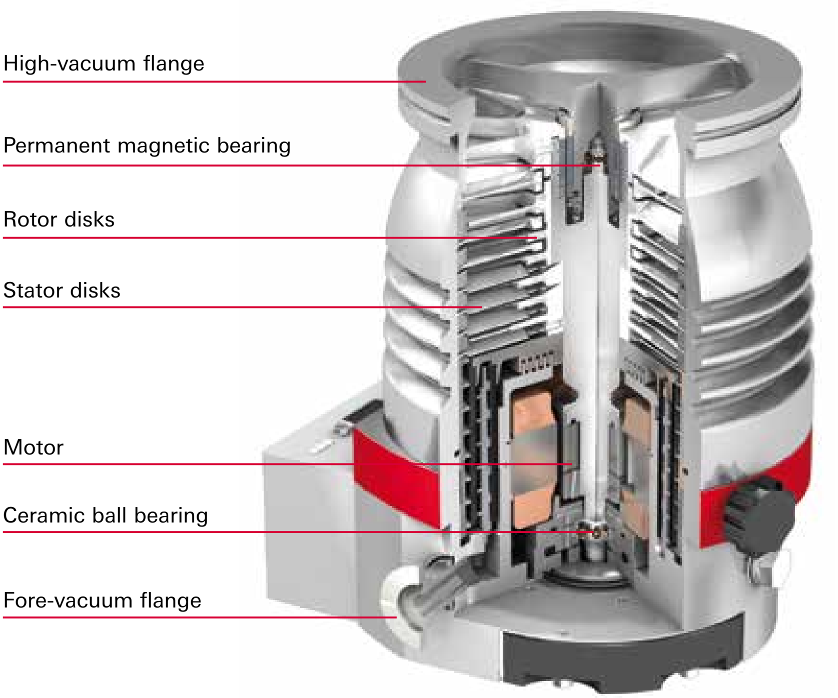


Figure 1: Sectional model of a hybrid-bearing turbopump showing the rotor shaft bearing arrangement with a permanent magnet bearing and a ball bearing.

The design of the turbopump is similar to that of a turbine. Inside the pump, several rotor disks are mounted on a shaft (Figure 1). Between them are stator disks whose blade orientation is mirror-inverted to that of the rotor blades. As a result, the gas molecules to be pumped are conveyed from the high-vacuum flange along the individual turbo stages to the fore-vacuum flange. The rotor of the turbopump is driven by a brushless three-phase synchronous motor. This enables very high rotational frequencies of up to 1500 Hz to be achieved. The rotor shaft bearing, in turn, consists of a permanent magnet bearing on the high vacuum side and a high performance ball bearing on the fore vacuum side. Although the ball bearing is minimally lubricated, the pump generates an oil-free vacuum.

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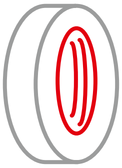
This hybrid bearing, which is rarely found in mechanical engineering, represents a special feature to the bearing and thus balancing technology and differs from usual bearing technologies. In combination with the very high speeds, balancing the turbopump rotors in particular is a technological challenge. This is because the balancing quality in particular has a major influence on the service life and performance of the turbopump.

Background to rotor balancing

In practice, every rotating component exhibits a certain amount of unbalance, which cannot be completely avoided. In order to enable operation with as little vibration as possible later on, it is essential to reduce the unbalance of the ever faster rotating rotors by taking appropriate measures. The best-known process is probably that of balancing car tires. If the wheels exhibit an imbalance, this becomes noticeable through vibrations on the steering wheel. This physical phenomenon is also known as centrifugal force: The DIN ISO definition describes the unbalance of a rotor as a condition in which oscillating forces and movements are transmitted to the bearings due to unbalanced centrifugal forces.



Even bodies that appear visually symmetrical in reality exhibit slight inequalities in the distribution of mass. This can result, for example, from the manufacturing process of the component or an inhomogeneity in the density of the raw material. The term unbalance describes this uneven mass distribution. Other causes can stem from the design or assembly. In addition, unbalance can also occur during operation due to wear or deposits. The condition of unbalance can be described using the example of a disk-shaped rotor with minimal axial extension (Figure 2). This rotor rotates with the angular frequency ω. Each mass particle m_i generates a centrifugal force $\vec{r}_i$ as a function of its radius $\vec{F}_i$, the direction of which is given by $\vec{r}_i$:

$$\vec{F}_i = m_i \cdot \vec{r}_i \cdot \omega^2$$

Equation 1

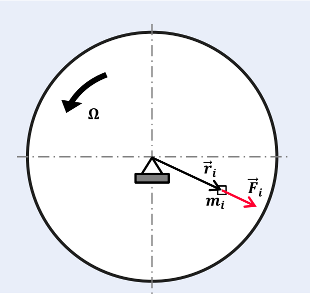


Figure 2: On a disk-shaped rotor, each mass particle generates m_i a centrifugal force $\vec{F}_i$. With a fully balanced mass distribution, all centrifugal forces cancel out during rotation.

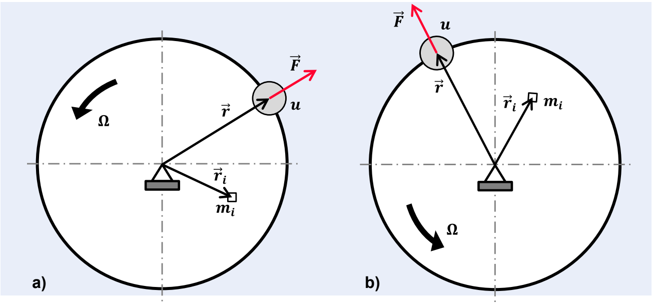


Figure 3: The unbalance condition of a disk-shaped rotor can be described by a single unbalance $u\vec{r}$ can be described (a). Due to the rotation, the circulating centrifugal force results in vibrations (b).

The vectorial sum of all individual centrifugal forces $\vec{F}_i$ gives the resulting centrifugal force $\vec{F}$, which acts on the bearing of the rotor:

$$\vec{F} = \sum_{i=1}^{n} m_i \cdot \vec{r}_i \cdot \omega^2$$

Equation 2

If there is now a resultant centrifugal force ($\vec{F} \neq 0$) then the rotor has an unbalance (Figure 3). This condition can be described by a single unbalance $u\vec{r}$, which corresponds to the resultant centrifugal force $\vec{F}$:

$$\vec{F} = \sum_{i=1}^{n} m_i \cdot \vec{r}_i \cdot \omega^2 = u \cdot \vec{r} \cdot \omega^2$$

Equation 3

Eliminating the influence of speed on both sides of the equation results in the following formula for calculating the unbalance $\vec{U}$:

$$\vec{U} = \sum_{i=1}^{n} m_i \cdot \vec{r}_i$$

$$= u \cdot \vec{r}$$

Equation 4

where the unbalance is given in kg - m or usually in g - mm.

Based on the example, it is clear that undesirable rotating forces arise when a body with unbalance is set in rotation (Figure 3b). The resulting forces depend on the rotational speed as well as the height of the unbalance. They lead to an additional load on the bearing and higher wear. In addition, vibrations are

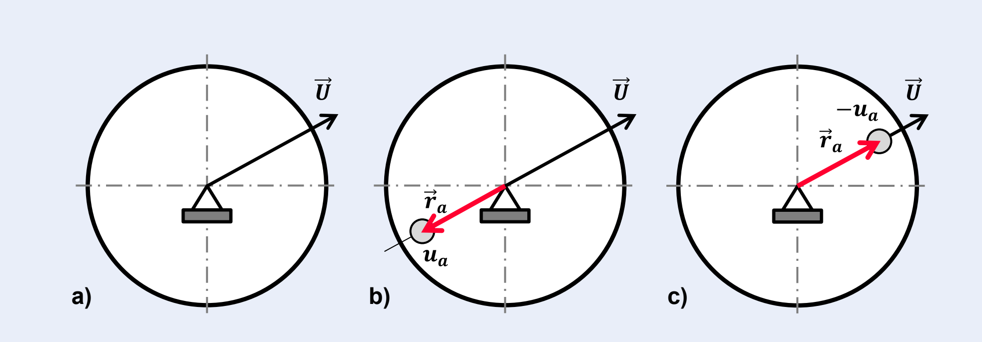


Figure 4: A disk-shaped rotor exhibits an unbalance $\vec{U}$ (a). This can be corrected by applying the additional mass $\vec{u}_a$ in the opposite direction (b) or by removing the mass ($-\vec{u}_a$) in the same angular position (c).

generated which are transmitted via the bearing to the housing as well as other mechanically connected components. These vibrations can also cause damage.

The rotors of turbopumps reach speeds of up to 90,000 revolutions per minute or 1,500 revolutions per second. Since the resulting forces increase quadratically with increasing speed (equation 3), the requirements for minimizing unbalance are extremely high. The slightest imbalance in the range of a few milligrams can already have a strong influence on the operation of the pump. Accordingly, good balance quality is crucial for the smooth running of the rotor and for years of damage-free operation of the turbopump. It also ensures minimization of vibrations transmitted to the vacuum chamber and the customer application.

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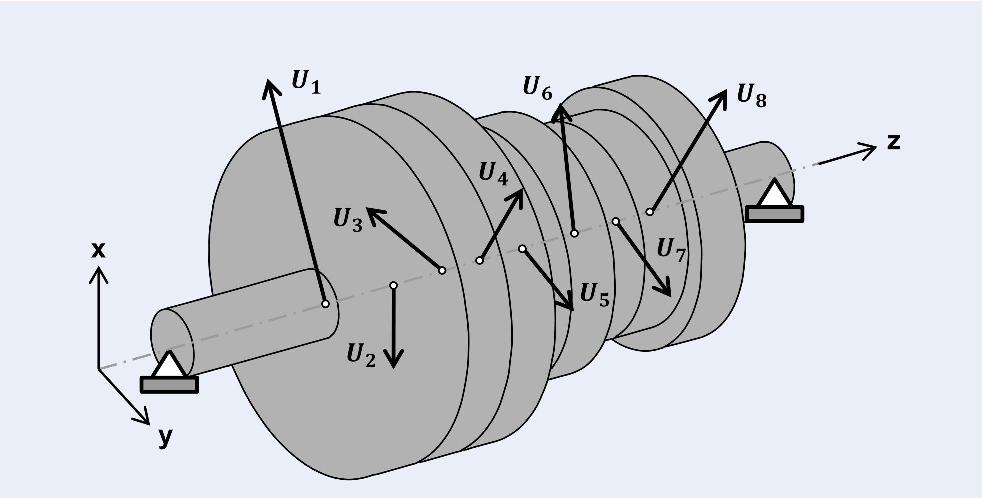

Figure 5: The unbalance state of a general rotor is described in this example by eight disk-shaped rotor elements, each of which has its own unbalance vector U_i in each case.

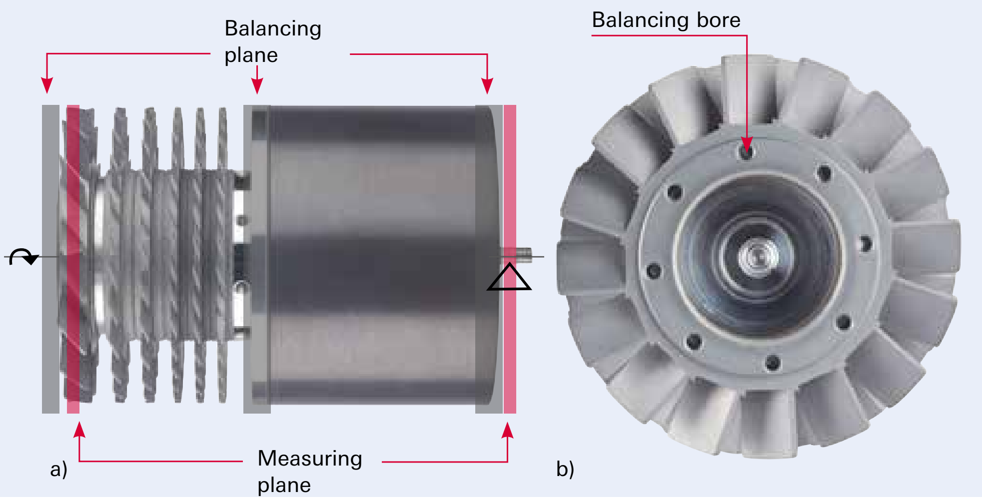

Figure 6: Illustration of a conventionally balanced turbopump rotor: a) Position of the measuring and balancing planes, b) Illustration of a balancing plane perpendicular to the axis of rotation with corresponding holes for accommodating the balancing weights

Conventional rotor balancing

Technically, it is impossible even today to manufacture a rotor without unbalance. The causes described for the occurrence of unbalance make it clear that every rotor has its own unbalance distribution - even in series production. Unbalance tolerances determine whether the mass distribution of a rotor is in order. Checking and correcting the mass distribution of a rotor are described by the process of balancing. Unbalance can be corrected by applying or removing mass in a correction plane perpendicular to the rotor axis (Figure 4), so that the following holds true

$$\vec{U} + u_a \cdot \vec{r}_a = 0$$

Equation 5

From equation 5 it is clear that the product of correction mass and correction radius must be $\vec{r}_a$ corresponding to the existing unbalance $\vec{U}$ of the rotor. In this case, the correction of the mass distribution can take place in the same angular position of the unbalance, or in the opposite direction.

In conventional balancing technology, additional mass is applied, which leads to correction - similar to the balancing of car tires. Here, balancing weights are screwed into special holes on the opposite side of the unbalance (Figure 4b). Another popular method is mass correction by removing mass in the same angular position of the unbalance with the aid of machining processes (Figure 4c). This includes, for example, grinding away material or removal by drilling or milling.

Since the rotor has a certain axial length, the unbalance condition of a general rotor is now considered in three dimensions. An infinite number of unbalances can occur along the rotor axis. Since the real unbalance cannot be measured in practice, the general rotor is decomposed into several rotor elements. These in turn correspond to disk-shaped rotors (Figure 5). The unbalance state of the general rotor is thus described with reasonable accuracy by a finite number of unbalance vectors $\vec{U}_i$ of all rotor elements. Mass balancing is then performed in one or more correction planes (also called balancing planes), depending on the unbalance state.

In conventional balancing, the rotor is mounted in a special balancing system and accelerated to special fixed balancing speeds. Due to the unbalance, centrifugal forces are generated in the bearings, which in turn cause the rotor to vibrate. With the aid of distance sensors, the radial deflections caused by the vibrations are measured in the measuring planes of the two bearing positions (Figure 6a). The resulting unbalance vectors $\vec{r}$ are determined from the radial deflections $\vec{U}$ with the aid of a proprietary calculation algorithm and the so-called influence coefficient matrix A:

$$\vec{U} = -A^{-1} \cdot \vec{r}$$

Equation 6

At the beginning, these coefficients must be determined by screwing in several test unbalances, depending on the rotor. For this purpose, specified test weights with known mass are mounted at defined positions in the rotor and the reactions are measured. Using the radial deflections of the individual measurements and the screwed-in test unbalances, the required matrix with the individual influence coefficients can be calculated. These then describe the system from the given real rotor and the balancing system. They are valid for all series rotors with the same geometry or the same design.

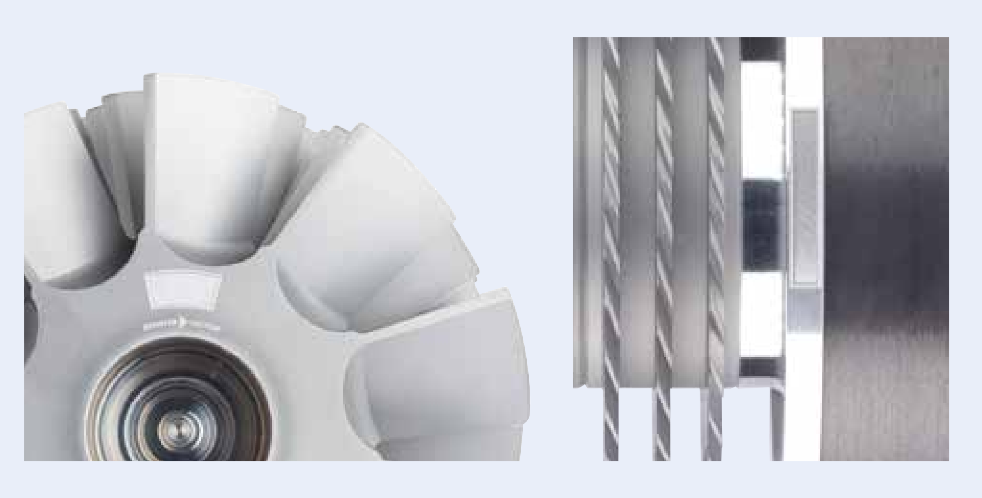

Figure 7: Photos of the segment geometry after laser ablation in two different balancing planes.

In order to reduce the total unbalance of the rotor, it is divided along the axis of rotation into several balancing planes perpendicular to the axis. To accommodate the balancing weights, holes are drilled radially around these planes in the rotor. The defined positions of the balancing holes are referred to as a fixed location balancing. The balancing algorithm determines the balancing weights for each balancing plane and usually divides them into two components each. Balancing weights are then screwed in manually along the circumference of the individual planes. The uneven mass distribution of the rotor is reduced - and with it the remaining unbalance. The specified tolerances are thus maintained. The unbalance is determined during the entire process at different speeds and gradually corrected. This enables a vibration-reduced run-up of the rotor to nominal speed.

The Laser Balancing Method

The requirements for turbopumps are divided into primary and secondary properties. While the primary properties concern pump performance, the application requirements for turbopumps have also been increasing in the area of secondary properties since the last decade. The high-speed rotors are therefore subject to continuous further development. This includes, among other things, the service life of the rotor, vibroacoustic emissions and cleanliness with regard to the outgassing behavior of the components and surfaces. Vibroacoustic emissions are sound and vibrations emitted by the pump at the housing. The main cause of increased vibroacoustic emissions is rotor imbalance. The novel laser balancing system remedies this problem and enables turbopump rotors to be balanced even more efficiently. The conventional balancing process is optimized by dispensing with balancing holes and weights. The complete automation of the balancing process also plays a key role here.

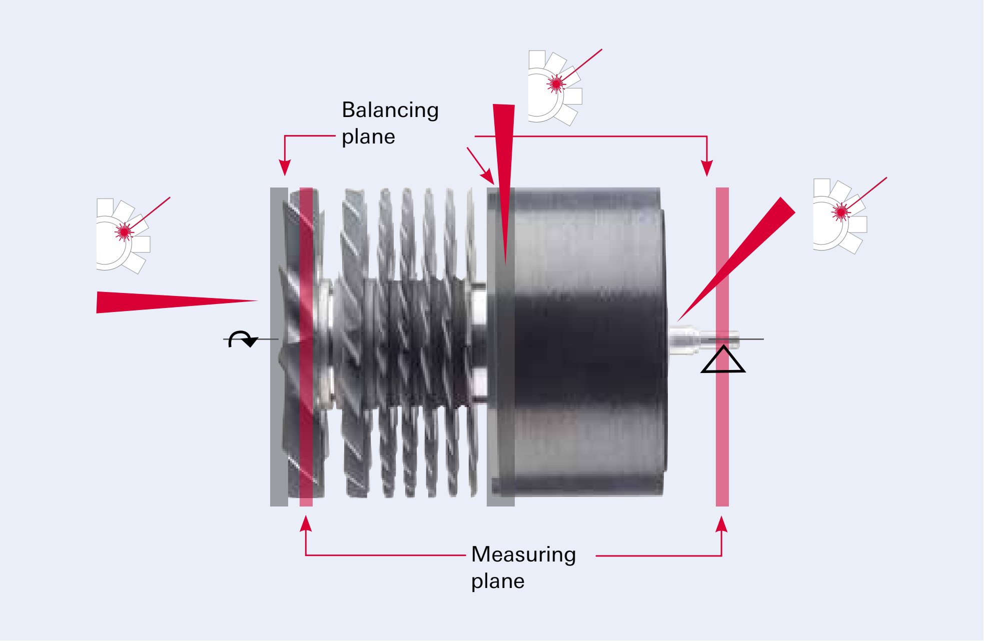

Figure 8: Illustration of a laser-balanced turbopump rotor showing the measuring and balancing planes as well as the schematic representation of the laser beam direction.

To begin with, the rotor to be balanced is mounted in the automated laser balancing system. Inside the system, the laser is encapsulated in a special chamber. This means that there is no danger to the environment from the laser radiation. Mass balancing as well as the individual steps for measuring and determining the unbalance are carried out iteratively at different speeds. This makes it possible to obtain a precisely and effectively balanced rotor in all speed ranges. As in conventional balancing, the radial deflections of the turbopump rotors are measured using distance measuring sensors in two measuring planes near the bearings. After the unbalance has been determined by the advanced balancing algorithm, the mass balance is then reversed. Material is removed by a laser at the same angular position of the unbalance vector. The unequal mass distribution is thus corrected. A high-energy pulsed laser beam heats the rotor material in the balancing planes locally to such an extent that a melt emission with vaporization and/or sublimation occurs. In this process, the material can be removed in the form of a defined segment geometry at any point along the circumference (Figure 7).

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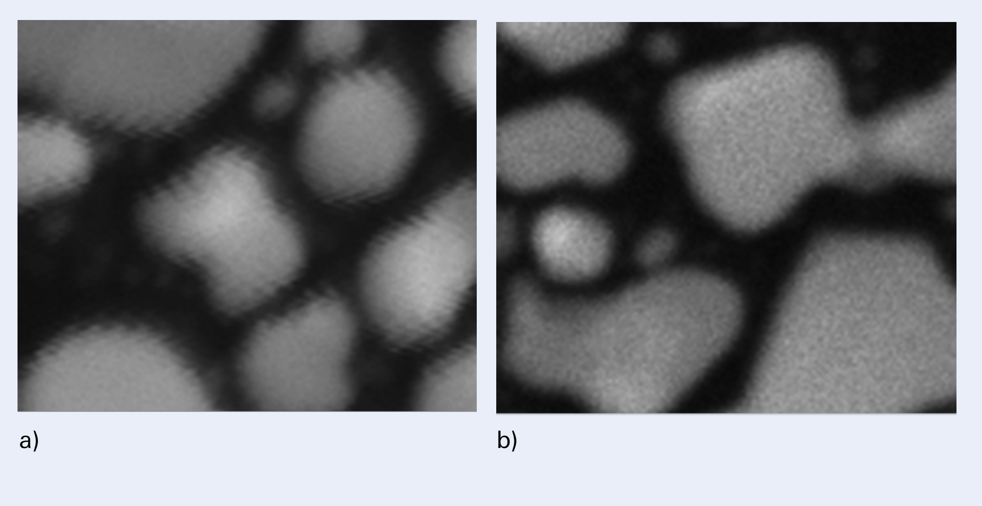
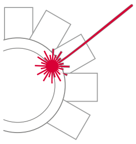

a)

b)

Figure 9: Comparison of two images of an electron microscope with integrated turbopump: a) Stronger vibrations (~20 nm) at the high vacuum (HV) flange result in a blurred image at high magnifications, b) Lower vibrations (~5 nm) achieve a sharper image (images courtesy of TESCAN, Czech Republic)



Compared to conventional balancing, in which graduated balancing weights are screwed in or masses are milled or drilled away, laser ablation works much more precisely. As a result, a significantly lower residual unbalance can be achieved. The material properties are not affected. In combination with a mirror system that can be moved relative to the laser, even a single processing laser reaches the different balancing planes (Figure 8). This results in greater flexibility in the design of new rotors and the definition and alignment of the balancing planes.

The absence of geometrically defined balancing holes and the precision of the laser allow any position of the ablation segment in the first balancing pass. This corrects the uneven mass distribution exactly in the necessary angular position of the individual balancing planes. Within the subsequent balancing passes, the algorithm of the balancing system takes into account the ablation segments already processed and places additional segments accordingly.
As soon as the residual unbalance over the entire speed range has been corrected in accordance with the tolerances, the rotor is removed from the automated system.

Advantages of the Laser Balancing Method

In many devices and applications with integrated turbopumps, low vibrations and/or quiet running of the rotors are a prerequisite for their operation. Laser balanced rotors therefore represent a major advance for their areas of application. In combination with the underlying calculation algorithms, they ensure more efficient correction of residual unbalance in a modern, automated balancing system: If the residual unbalance U_{Rest} is reduced, this also has an influence on the balancing quality class of the rotors. In this context, a well-balanced rotor with a high balance quality means a low amount of balance quality class G. ω: speed of the rotor [Hz]; m: mass of the rotor [kg] and G: usually in mm/s.

$$G = U_{\text{Rest}} \cdot \frac{\omega}{m}$$

Equation 7

Turbopumps with laser-balanced rotor have a longer service life and transmit less vibration to the pump housing.

Based on the unbalance tolerances, this reduces the residual unbalance and therefore the balance grade by about 50%. Centrifugal forces induced by unbalance are thus minimized. The rotor material and, in particular, the bearings are thus subjected to less stress. For this reason, turbopumps with laser-balanced rotors have a longer service life.

In addition, lower vibrations are transmitted to the pump housing via the bearing. During operation, this has a positive effect on the noise emission of the pump and sensitive components or processes mechanically coupled to the turbopump. Particles generated during laser ablation are already extracted and filtered during the process. Furthermore, the subsequent cleaning of the laser-balanced rotor guarantees maximum surface cleanliness.

Application examples are ion mobility spectrometers, which are used as benchtop devices on laboratory workstations. In this context, low-noise operation of the integrated turbopump is required. Another example is electron microscopes, which enable sharp high-resolution images only through a vibration-optimized rotor and low vibroacoustic emissions (Figure 9).

The described advantages of innovative laser balancing illustrate the technological progress of laser-balanced rotors compared to conventionally balanced rotors. With extended rotor life and reduced vibration and noise emissions from the turbopump, the process represents another milestone in vacuum technology and offers greater flexibility for the design of new turbopump rotors.

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