Understanding—and Improving—Vacuum Chucking Systems

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The use of a vacuum chucking system opens a variety of options that simply are not available using traditional methods of holding objects on a lathe. Vacuum chucking solves one of the most common and frustrating problems in woodturning: efficiently finishing the bottom of a turned piece, allowing the turner to eliminate the mounting tenon to shape a seamless platform or foot. Reverse turning with a vacuum eliminates the need for a scroll chuck or jam chucking when putting the final touches on a bowl.

Moreover, vacuum chucks can hold natural-edge bowls with irregular rims and do not require the use of padding to prevent marring a finished surface. They also allow the turner to remount finished pieces for touch-up sanding, minor reshaping, and repairing slight dings or scratches.

Vacuum systems operate on a simple but profound premise. By creating an area of reduced pressure (a vacuum) with a vacuum pump, they utilize the earth's atmospheric pressure to hold a piece against a hollow mandrel in the headstock. To be precise, the vacuum does not pull the bowl against the chuck; rather, the outside pressure pushes the bowl. The amount of force applied depends on the difference of the pressures inside and outside the system.

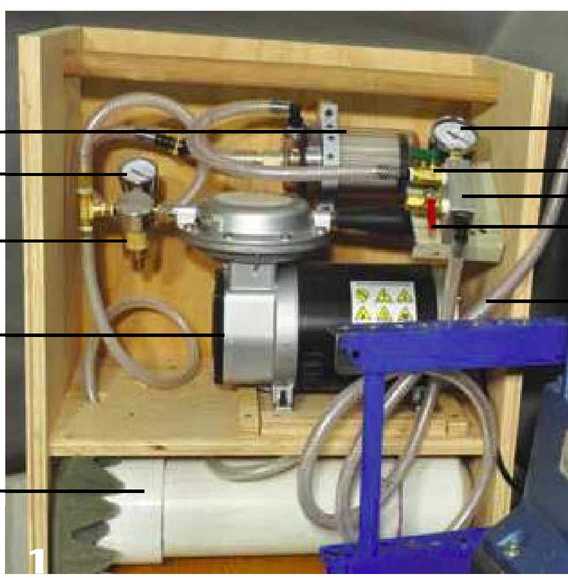
Recognize that as the size of the chuck increases, the force against the bowl will increase for the same applied vacuum. Most vacuum systems will have a control valve that can be opened to increase the leakage, thereby reducing the vacuum. Otherwise, the force generated against a large thin bowl could crush it.

Vacuum systems have the advantage of being fast, easy to use, versatile, and reusable.

A basic vacuum chucking system contains:

- A vacuum pump that generates the vacuum. Such pumps are available through woodturning catalogs but can also be found in surplus stores and on Internet auction sites. Many vendors sell complete kits and the plans to make installation easier.
- Filters to protect the pump from dust and dirt ingested during operation
- Adjustable valves and gauges to control the vacuum level
- A flexible hose and rotary coupling to provide a leak-proof connection between the stationary vacuum pump and the hollow headstock spindle
- A hollow vacuum chuck with an airtight sealing material around the rim. The chuck can be made from many different materials, such as metal, PVC pipe, or even close-grained wood, and is usually threaded directly onto the spindle.

When the vacuum pump, via the valves and rotary coupling, removes the air from within the chuck, a region of reduced air pressure is created between the chuck and the turning. Since the air pressure on the outside of the piece is greater than that on the inside, a force is created that pushes the bowl into and against the vacuum chuck.



The vacuum system used for this article.

It should be noted that vacuum systems, while convenient, have some drawbacks. Porous or open-grained wood will allow air to pass through the walls of the turning and the bowl may not be held securely. Thin-walled turnings can be crushed if pressure is too high. And, vacuums will not hold as securely as a faceplate or a four-jaw chuck.

The problem of leakage

When I decided to upgrade my lathe by adding a vacuum chucking setup, I found many good articles describing how to *assemble* systems. Most descriptions of vacuum systems, however, failed to emphasize the importance of eliminating air leakage. Leakage can cause significant reduction in performance to the point of having undesirable consequences.

My engineering background told me that something was missing. All of these systems work and are successful, but the terms used to describe the systems and the descriptions of the operation were not always accurate. Furthermore, all the articles missed an important point. *The key to understanding a vacuum system and getting the most out of it is to control the leakage of air within the system.* Several authors suggest measuring the leakage by using the static reading of the vacuum gauge while the pump is running, but that is not a true indicator of whether there is leakage. This article will help you work with the system you already have, or will build, so that you better understand how and why it works and how to get the best performance from it.

I will offer an analogy to help explain some of the concepts of a vacuum system. Let's say Monty and Dave take Monty's boat out to do some fishing. Dave is a cautious guy and asks Monty if ▸

The rotary vacuum adapter (coupling) is shown inserted into the spindle in the center of the hand wheel at the outboard end of the headstock.

A small bowl is mounted onto the lathe using a vacuum chuck. This is the configuration utilized to clean up and finish the bottom of the bowl. This same setup is used for the fall-off test when looking for leakage.

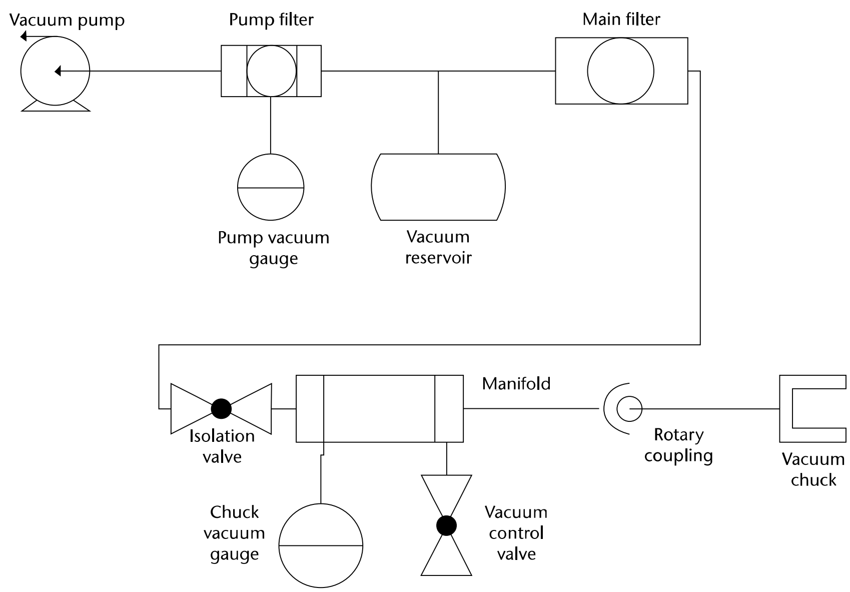


Figure A. Schematic diagram of the system in *Photo 1*. The isolation valve and vacuum reservoir are optional but recommended.

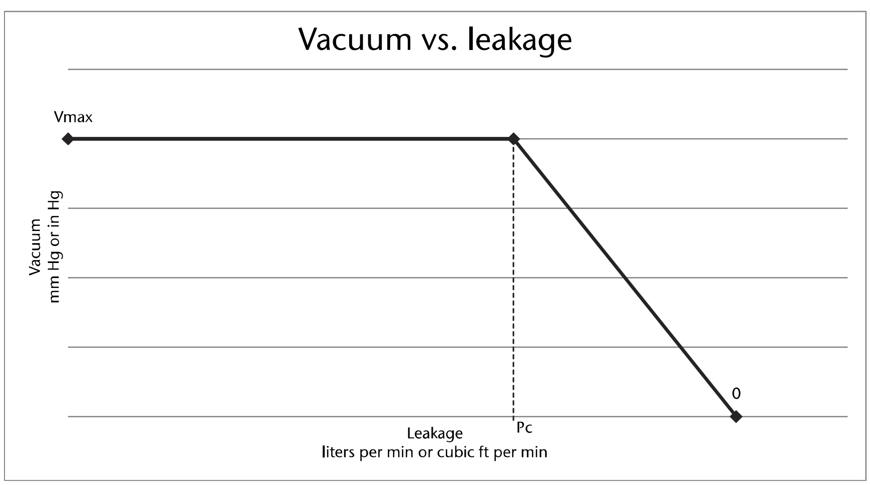


Figure B. The graph shows the relationship between the achieved vacuum and the system leakage. When there are no leaks, the vacuum will be at the maximum, Vmax. As the system leakage increases, the measured vacuum will stay near Vmax until the pump capacity, Pc, is reached and then it will decrease toward zero.

the boat has any leaks. Monty does not think so, but opens a hatch and looks into the bilge, reporting, “It’s a little damp down there but nothing to be concerned about.” Dave notices that the bilge pump is running and asks, “Is the water level in the bilge low because there are no leaks or is it because the pump is ejecting water as fast as it comes in?” To find out, Monty turns off the bilge pump and the water level starts to rise, indicating a leak. He turns the pump back on and starts looking for the leak.

A vacuum pump corresponds to the bilge pump and the vacuum gauge reading corresponds to the water level in the bilge. In the boat, the severity of the water leak can be categorized as slow or fast. Likewise, for a vacuum system the rate of change of the vacuum reading, under the right conditions, allows us to classify the leakage as fast or slow. These are not exact measurements but can still be useful.

When the vacuum pump is running and the vacuum gauge shows the maximum reading for that system, it does not indicate whether there is a leak. As long as the leakage rate is less than the pumping capacity of the pump, the gauge reading will stay at the maximum. Only when the leakage exceeds the pumping capacity will the vacuum level start to drop. This is the way that the control valve contained in most chucking systems reduces the vacuum level, by manually increasing the leakage.

By understanding these concepts, you can use them to characterize your system, identify any leakages, and take appropriate action.

Review of vacuum chucking systems

A good place to begin is with a review of a vacuum chucking system *(Photos 1, 2, 3, Figure A)* and a discussion of how each part relates to air leakage. The system pictured is a common system, with the possible exception of the isolation valve, a reservoir, and an additional vacuum gauge.

Figure B shows the general relationship between the vacuum generated within the system and the air leakage into it. For an ideal system, the leakage will be zero and the vacuum will reach its maximum. At sea level, the maximum vacuum will on average be 14.7 pounds per square inch absolute (psia) or 29.9" of mercury (29.9" Hg) or 760 mm Hg. The actual maximum vacuum in your case will depend on the altitude and the barometric pressure of your location.

As previously noted, the leakage rate in actual practice is not zero, so the vacuum will always experience some reduction. As long as the leakage is less than the pump’s capacity, the vacuum will be at or near the maximum. As the leakage starts to exceed the pump’s capacity, the vacuum starts to decrease toward zero. Note that the pump’s capacity is the key to when the vacuum starts to decline. This will affect your decision on the desired capacity of your pump. I will expand on this factor later.

You may be wondering why the vacuum does not drop immediately to zero when the leakage starts to reach the rated pumping capacity. First, the pump’s pumping rate depends on the pressure from which it is pumping and results in a curve that drops off gradually. Second, the leakage through the control valve or the wooden bowl is dependent on the differential pressure across it. As the vacuum drops (the differential pressure), the flow rate will decrease. These two factors will interact, eventually balancing to provide a relatively smooth transition from full vacuum to ambient or zero pressure.

Controlling the leakage is the key to understanding and getting the best performance from your system. Sources of leakage include:

1. Pipe thread connections
2. Hose or tubing connections
3. Filter seals
4. Pinholes in reservoir or hoses

4 A C clamp is being used to temporarily close off the tubing to isolate the rotary coupling from the rest of the system.

5 To test for bearing leakage through the vacuum coupling, a plastic plug can be inserted into it.

6 The chuck to bowl seal is achieved here by utilizing sheet craft foam.

7 To test the overall system for leakage, an aluminum sheet is placed over the vacuum chuck. It tests the seal on the vacuum chuck as well as all other components and connections.

To test the seal of the vacuum coupling with the spindle, seal off the end opposite to the coupling. In this case the seal was achieved by wrapping Teflon tape around a solid Morse taper and inserting it into the spindle.

5. Bearing seals in the rotary connector
6. Valves
7. Vacuum-chuck-to-spindle interface (headstock threads)
8. Vacuum chuck body
9. Setting of the vacuum control valve
10. Interface material between vacuum chuck and bowl
11. Pores through the body of the bowl

This list can be separated into three categories:

A. Stable leakage fixed by design or construction, items 1 through 8
B. Variable, set by operator, item 9, control valve
C. Variable with limited control, items 10 and 11

For vacuum systems, we need to keep leakage below the pump's capacity (Pc) for the system to work properly. Leakage group A can be tested and remedied once and should be stable with infrequent need for repairs—we want to drive this leakage to the lowest possible levels. Leakage group C is the most difficult to consistently control. Even though we turn the surface of the bowl smooth and round, there is no guarantee that it will stay that way. It may warp over time. The body of the bowl may leak because of wormholes or porosity, cracks seen and unseen, and worn gaskets may also be an issue.

Assuming that the leakage through the control valve is set to zero, then the sum of the leakage from groups A and C should be less than the capacity of the pump. The difference between this leakage and the pump capacity is the margin of operation for the system. The margin of operation will change with each bowl, sometimes a lot and sometimes a little. The control valve operates within this margin to control the final vacuum applied to the bowl.

In a perfect system, the leakage will be zero and the size of the pump is not much of a concern. In a real system, the major source of leakage should be the leakage associated with the woodturning itself. Consequently, for a given bowl, the system margin of operation is directly related to the capacity of the pump. The sizing of the vacuum pump is not dependent on the size of the bowls to be turned, rather it is dependent on the leakage both between the chuck and the bowl and through the bulk of the bowl. When selecting your vacuum pump, the most important specification is the capacity of the pump measured in cubic feet per minute, not the horsepower or the maximum vacuum developed.

Testing for leaks

We may not be able to measure the leakage directly but we can quantify it indirectly. Remember the rising water level in Monty's boat when the bilge pump was turned off? When you have a bowl on your vacuum chuck and turn off the pump, the reading on the vacuum gauge drops toward zero. (Be sure the lathe is not running; the bowl will detach.) Sometimes the reading drops quickly; other times it is slower. With the control valve completely closed, this fall-off of the vacuum can be used to get some idea of the rate of leakage. The faster the rate of decrease in vacuum, the larger the leakage.

To maximize the performance of the vacuum chucking system, we need to find and reduce any leaks within it. The challenge is to do this without a lot of expensive specialized equipment. Our tool set includes the vacuum pump, valves, vacuum gauges, plugs, and clamps. Our strategy is to divide and conquer. Isolating different sections of the system, and monitoring the vacuum rate of fall when the vacuum is cut off allows us to locate and fix leakages.

Isolating leakage

Most systems are built using flexible plastic tubing. Using a piece of scrap tubing the same as that used in your system, verify that you can apply a clamp, closing it off without permanent damage *(Photo 4)*. The tubing should recover upon removing the clamp. This may be used to temporarily close off or isolate a section of the system. A suitable plug for shutting off the end of a tube can be fashioned from a tapered cap from a tube of caulking *(Photo 5)*.

The isolation valve in the system shown is also useful in isolating sections. When tracking down and fixing leaks, fix the largest ones first. Until the large leaks are fixed, small leaks ▸

For this system, it was found that using Teflon thread sealing tape on the spindle significantly reduced the leakage.

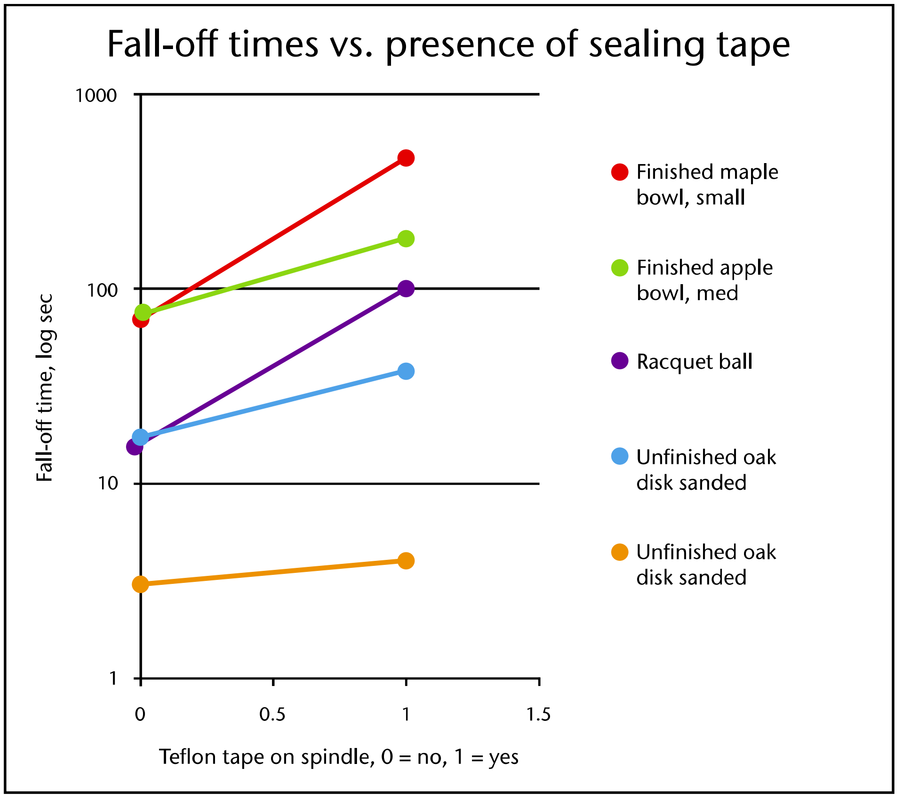


Figure C. The graph shows the change in time for various items to fall off the vacuum chuck. On the horizontal scale 0 indicates no Teflon tape was used on the spindle threads whereas 1 indicates that tape was used *(Photo 9)*. Without the tape, the system leakage "swamped out" leakage of the item being held. With the tape, the system can hold items that otherwise could not be mountable. Note the nonlinear scale on the vertical time axis.

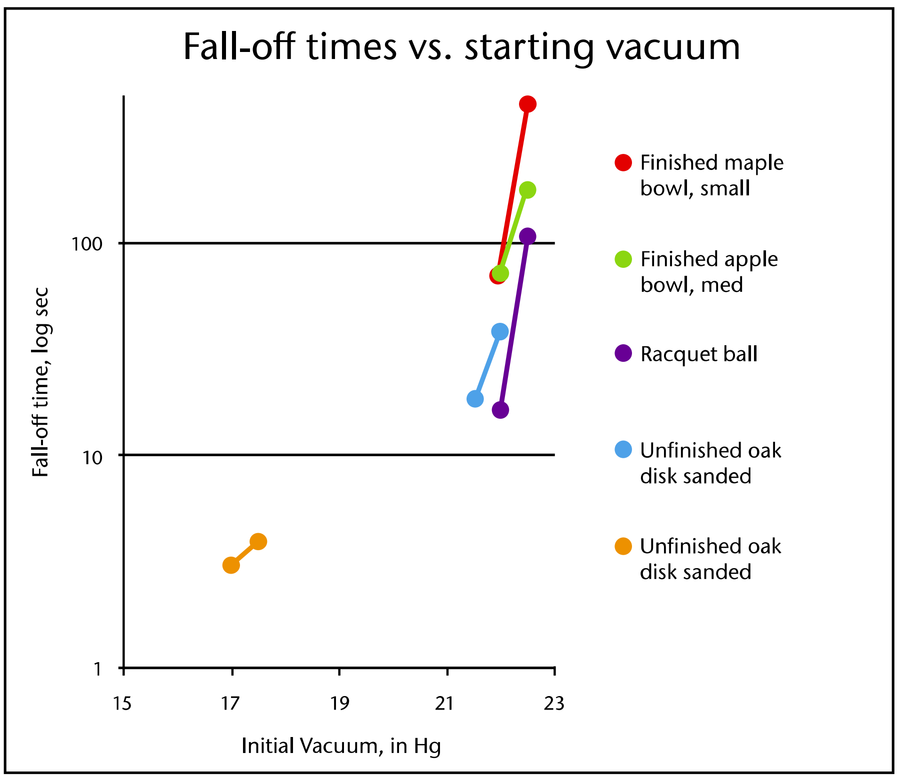


Figure D. When a leaky object is mounted, the vacuum achieved may be less than otherwise achievable. This graph illustrates that when system leakages are reduced (see *Figure C*) the initial vacuum improves and the fall-off time increases indicating that the system-operating margin has increased.

will be hidden by the effects of the larger ones.

What should be expected in the rate of decrease in vacuum for an isolated section? For the system used in this article, the isolation valve was closed and the pump was turned off. The pump vacuum gauge read 520 mm Hg and stayed at that reading for more than five minutes without detectable change. This verified that there were no significant leaks between the pump and the isolation valve including the filters and the vacuum reservoir. In contrast, when the tubing was closed off between the manifold and the rotary coupling and the isolation valve was closed, the reading on the chuck vacuum gauge dropped to zero quickly. The leakage was traced to a faulty vacuum control valve. Note that without this kind of test, the faulty valve would not have been easily found. After replacing the faulty control valve, I repeated the test. The vacuum reading held for more than five minutes with no observable change.

Most vacuum chucks have a flat surface with gasket material upon which the bowl is mounted *(Photo 6)*. By placing a sheet of aluminum or other stiff smooth flat nonporous material across the chuck, the entire system can be evaluated *(Photo 7)*. Close the isolation valve and observe the change in the chuck vacuum gauge. Do not expect zero leakage at this point but the leakage should be reasonably gradual: vacuum drops to zero over several minutes.

By placing a small nonporous rubber ball inside the vacuum chuck, you may be able to separate out the effects of any leakage through the body of the chuck. Then, plugging the end of the spindle will allow evaluation of the leakage through the chuck's mounting.

Making a measurement with the spindle plugged and then a measurement with the tubing between the manifold and the rotary coupling blocked will help isolate the leakage contribution of the rotary coupling *(Photos 8, 8a)*.

Fixing the leaks

When a leak is found, fixing it may be simple or it may require ingenuity. Here are a few ideas that may help.

- *A hose barb leaks where it is screwed into another fitting.* Use Teflon tape to seal threads. Sometimes taping does not work, in which case try using silicone sealant on threads before insertion and tightening. After the silicone has set up, do not readjust the threaded connection; you may need to reapply the sealant.
- *Hose to hose barb leakage.* Use a hose clamp.
- *Valve leakage.* Some valves can be tightened with a nut at the stem; otherwise replace the valve.
- *Reservoir leakage.* Seal on the outside with silicone sealant.
- *Vacuum chuck leaks where mounted on spindle.* Sometimes a plastic washer slipped over the spindle will seal the space between the chuck and the shoulder on the spindle. Also, use thread-sealing tape on spindle threads *(Photo 9)*.
- *Leakage through body of vacuum chuck.* If the chuck is made from wood, then seal it with polyurethane finish. If using O-rings, check that they are present and properly seated. Replace if needed.
- *Leakage at interface between chuck and bowl.* Check and repair gasket material. Sometimes using a second layer of closed-foam gasket material will help. Repair contact surface of bowl to better fit chuck.
- *Leakage through body of bowl.* Place painter's tape over wormholes and cracks on the outside of the bowl. For more extensive leakage, try wrapping the exterior with plastic film. Leave the area to be turned or finished exposed.
- *Rotary vacuum adapter leakage.* Apply grease to the O-rings used to form a seal between the adapter and the inside of the spindle shaft. Be sure that the grease used will not degrade the O-rings. Check the bearings for leakage, replace any leaky bearings. Check all gaskets used with the adapter, and replace if needed.

Performance of the system

Be aware that things can change while finishing the bowl. Check the chuck vacuum gauge frequently. The bowl may have shifted, a crack developed, you cut into an unknown flaw, or you may have sanded through the bottom.

For the vacuum chucking system used in this article, with the lathe off, a finished bowl was placed on the vacuum chuck and the isolation valve was closed *(see Photo 3)*. Before the valve was closed the vacuum read 22" Hg. Upon closing, the vacuum decreased and the bowl fell off in 66 seconds. The system was then investigated using the techniques outlined earlier. A major source of leakage was found at the spindle threads. Teflon sealing tape was wrapped around the spindle threads and the vacuum chuck replaced. The fall-off test was repeated. The time for the bowl to fall off was increased to over six minutes.

Several authors have indicated that bowls made of porous woods, such as oak, cannot be mounted on a vacuum chuck because the porosity of oak causes too much leakage. A more accurate statement would be that the total leakage may exceed the capacity of the system. Perhaps, by fixing the fixable leaks, the system capability is extended to allow the leaky bowls to be mounted. Monitoring the vacuum readings can indicate whether the achieved vacuum is adequate to hold your leaky bowl.

Figures C and D are enlightening and illustrate some interesting points:

1. The static vacuum level when the pump is running is *not* a good indicator for the presence or absence of leakage.
2. If the leakage is less than the pump capacity, the vacuum level can be high and look normal.
3. When the pump is turned off or isolated, the rate of vacuum decrease is a good indicator of the relative leakage rate.
4. The leakage along the spindle threads was a major source in this system. Yours may vary.
5. Excess system leakage can prevent mounting items that would otherwise be mountable. With care, even leaky wood can be mounted and turned. Try it—but with care.
6. A leaky system requires a larger pump capacity than one whose leaks were minimized.

Safe vacuum levels

I have been asked, "Knowing that the forces increase with larger chuck sizes, what is a safe vacuum level to use?" It is difficult to give an exact answer. There are two answers. One relates to the force generated to hold your bowl on the chuck. Force calculations are shown in the sidebar. The other answer relates to when the force generated will crush your bowl.

As you know, wood is not an ideal engineering material; it has flaws, wood changes with temperature and humidity, and there are changes within a log and from species to species. Also, the shape of your bowl and wall thickness have a big impact. And, what happens if you get a catch?

An Internet article by Bill Marx, "Allowable Vacuum for Wood Turning," describes the various factors in determining the strength of wood (twistedturner.com/vacuumchuck). Since the thickness and shape of your ▸

item can vary greatly, he simplified the calculations by analyzing a disk ⅜" (9.5 mm) thick using the weakest grain orientation. The result is a chart indicating the allowable vacuum for different size chucks and types of wood. Marx's chart should be viewed as a guide and not an exact answer, yet the article (and the chart) is the best attempt I have seen to answer the question of a safe vacuum level. ■

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Here are links to an article and a discussion on the Internet that you might find helpful:

- Bill Marx: "Allowable Vacuum for Wood Turning," twistedturner.com/vacuumchuck
- Steve Schlumpf: "Vacuum Chuck System—How I Built Mine," February 2008, sawmillcreek.org/showthread.php?p=764151&highlight=vacuum+chuck+system+built+mine#post764151

Measuring Vacuum

When measuring vacuum and pressure, it is easy to get confused with terms: psi, psia, psig, mm Hg, inches Hg and others. These are just different ways of measuring the same thing. We have all worked with thermometers, some marked in degrees Fahrenheit (F), others marked in Celsius (C) and yet another marked in Kelvin (K). They differ in the size of the measuring unit and what they call *zero*. For Celsius, zero was defined as the freezing point of water; 100 degrees is the boiling point. For Kelvin, zero is *absolute zero*, where there is no molecular motion.

When measuring the level of vacuum, it is important to understand that a vacuum is a location where there is nothing; it contains no mass. The *best vacuum* is that of outer space, often called a hard, or absolute vacuum. When we have a location that contains matter such as a gas (air), the molecules bounce around pushing against anything present, such as the inside of a tank. This pushing by the moving molecules produces a force we call pressure. When we measure the pressure we use the units of force per unit of area. Using English units, it is pounds per square inch or psi. In metric, the unit of pressure is kg per square centimeter or in Pascal abbreviated Pa. (Look at the sidewall of the tire on your car. You will see molded figures giving the maximum recommended pressure in both psi and kPa, or kilopascal.)

Okay, now we have a unit of measure for pressure, but what is zero pressure? What do we use as a reference for zero? For psia, the *a* stands for absolute. So, psia means pounds per square inch absolute indicating that it is the pressure measured relative to a hard vacuum. At sea level, the weight of the air creates an average pressure of 14.7 pounds per square inch absolute or 14.7 psia, that is, relative to a perfect vacuum. This pressure at sea level is also referred to as one atmosphere or 1 atm. We are unaware of this pressure since it is the same for us on all sides so the net force cancels out to zero.

But wait, when looking at a pressure gauge lying on the table, I see 0 psi not 14.7 psi. What gives? To be precise, the gauge should be labeled 0 psig, where *g* stands for gauge. This gauge is using the ambient air around itself as the reference. So, it is saying it is measuring zero pressure difference relative to the surrounding air. Another way to look at this is to say that at sea level, 0 psig = 14.7 psia = 1 atmosphere = 101.3 kPa. These all mean the same thing, just different units of measure with different zero reference points.

Air pressure on the Weather Channel will be expressed as inches of mercury (in Hg). This is a holdover from the original mercury barometers. The height of the mercury in the tube is due to the pressure of the ambient air balanced against the weight of the column of mercury. This air pressure measurement of the ambient air is relative to that of a hard vacuum. The barometric pressure can be expressed as inches Hg or mm Hg. Realizing that the average absolute air pressure will decrease about 1" Hg for every 1,000 feet of altitude, readings taken at altitude are normalized to that of sea level for easier communications and predictions.

Now let's look at measuring a vacuum with a vacuum gauge. All measurements we are concerned with are relative to the ambient air pressure, so zero vacuum means that it is the same as the free air. Most vacuum gauges measure the differential pressure between ambient and that inside the system. Early studies of vacuums were performed using a glass tube in the shape of a U containing mercury. One end of the U was left open to the ambient air, the other was connected to the area evacuated, the vacuum. As the vacuum increased, the column of Hg in that side of the U rose while that open to the air fell. The amount of vacuum generated is measured by measuring the difference in height of the Hg in the two sides of the U. Modern vacuum gauges are still marked in inches Hg or mm Hg. If the vacuum gauges were marked in psig or Pa, then the readings would need to be negative numbers.

The maximum vacuum that can be generated at sea level is -14.7 psig = 29.9" Hg = 760 mm Hg. (Did you catch the minus sign?) Watch out for articles that quote a vacuum outside of these limits; it indicates a mistake somewhere. For example, a vacuum of 25 psi is an obvious error. Either the number is wrong or they are using the wrong units. Also, watch out for altitude effects. Here in northern Colorado the altitude is about 5,000 feet. The upper limit on the achievable vacuum would be around 24.5" Hg (29.9" Hg – [1.05" Hg/1,000 ft] × 5,000 ft = 24.65" Hg).

Typical mechanical vacuum gauges used in our shops are not precision devices and are not provided with simple methods for calibration. Also, because of the size of the dials and the graduations on those dials, they do not lend themselves to making precision readings. Despite these shortcomings, these gauges are useful in the context of this article—to set vacuum levels, to find and reduce leakages, and to detect changes over time in the performance of a system.

The force holding your bowl against the vacuum chuck is a function of the area of the chuck and the differential pressure between the inside and outside. The differential pressure is measured by the vacuum meter. For a circle, the normal shape of a chuck, the area = Pi times radius squared. The pressure is in inches of Hg or mm Hg (1" Hg = 0.491 psi). For a 2" chuck with a vacuum of 20" Hg, the differential pressure = 20" Hg × 0.491 psi/inches Hg = 9.82 psi. The area = 3.1415 square inches so the force of the bowl against the chuck will be: Force = 3.1415 × 9.82 = 30.85 lbs. Rounding off gives an estimate of 31 lbs of force holding the bowl against the 2" vacuum chuck. Similar calculations for a 4" chuck at 20" Hg will have a force of about 123 lbs pressing the bowl against the chuck.

This compound meter measures both pressure and vacuum. Pressure rotates the needle clockwise and is measured in psig or kg per centimeter squared. A vacuum rotates the needle counterclockwise and is measured in inches Hg or cm Hg. Note that switching units between pressure and vacuum can help avoid confusion.