On the Design of Ultra Precise Machine Slides

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Abstract

The slides or carriages used to provide high precision translational motion for measuring machines or optical quality machine tools present special challenges to the design engineer. In order to achieve the extreme accuracy of motion required, a great deal of attention must be paid to the smallest details of the design. This paper will concentrate on the principles of slide design and will more or less ignore the selection of feedback devices and drive mechanisms. Particular attention will be paid to the selection and design of the slideways and their bearings, as these have a profound effect on the performance of the completed mechanism.

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Sizing the slide

All of the decisions involved in designing precision slides are interdependent to some degree; therefore any description of the design process is an oversimplification. The usual starting point is to determine the size of the slide top, and the stroke or travel required. Do not design a slide which is larger than necessary. It is important to keep the natural frequency of the slide as high as possible, and that means that the moving member should be as light as possible. Large slides are more susceptible to thermal growth problems than their smaller brothers, and large slides are usually more expensive to manufacture.

Try to keep the center of gravity of the slide and the spindle or tooling which it will carry near the geometric center of the assembly, even if this means making the slide a little larger than would otherwise be necessary. Doing this distributes the load on the ways more evenly, making the design of the way system more straightforward.

If the slide is to use air bearings, it may have to be somewhat larger than would otherwise be necessary in order to accommodate bearings with adequate load carrying capacity. This is not usually a problem with other types of bearings, but the question should certainly be asked early on in the design process.

Weight trade-offs

The goal of having a slide which is as light as possible in order to achieve a high natural frequency is in conflict with the next requirement, which is to design a slide which is as rigid as possible. This, of course, is a classic trade-off which has plagued engineers for as long as there have been engineers.. Fortunately there are some materials available which may be of help, and their use should be considered. Ceramics may be used if the slide is small. Some ceramics have excellent mechanical properties, but the cost may be prohibitive for any but the smallest structures. Another, perhaps more useful approach is to use composite construction using light materials in low stress areas. The goal now becomes to design the lightest structure possible which will act essentially like a rigid body under the expected operating loads.

Aspect ratio

Avoid designing slides which are wider than they are long. If you have ever owned a chest of drawers which was very wide in relation to its depth you probably experienced what is often called the dresser drawer syndrome. When you push or pull near one end of the drawer, it sticks and jams in its tracks rather than sliding smoothly. While a short, wide slide is not likely to stick in position, it will exhibit the same yaw characteristics which cause the drawer to jam.

Do not go to the other extreme of long, narrow slides without understanding the consequences. Narrow slides can be susceptible to errors of roll which show up looking just like errors in straightness of travel, and straightness of travel is commonly one of the design goals. Long slides also carry a weight penalty which should be avoided if possible. Finally, long slides increase the size of the support structure required; this usually has an adverse effect on cost.

Choosing the bearing system

Once the size and shape of the slide have been selected, the next step is to choose the bearings to be used. Several different types of bearings are commonly used and each has its advantages and disadvantages.

Rolling element bearings

Ball or roller bearings can be used to support machine slides. The major advantage of this type of bearing is the low coefficient of friction, which minimizes the force required to move the slide. Static and dynamic coefficients of friction are almost identical; this minimizes the effects of stick-slip, which will affect the positioning accuracy of the slide and its control system.

There are several disadvantages to the use of rolling element ways. Great care must be taken to ensure that all of the balls or rollers which operate on a given surface are the same size within very close tolerances. Even five or ten microinches difference in the size of the elements can cause problems with straightness. Roundness of balls or rollers is, if anything, more important than size control. A single out of round element will result in a periodic perturbation in the straightness of the slide travel. The magnitude of the disturbance will be roughly equal to the two point roundness error divided by the number of supporting elements in the system. To visualize what is happening, think about each rolling element as a wheel with a rubber tire. Small tires are softer (more compliant) than large ones but the compliance of all wheels is very non-linear. Using a large number of small elements reduces the out of roundness problems, but increases the system's sensitivity to yet another problem.

Lightly preloaded elements do not crush the small particles of dirt which invariably contaminate the way surfaces. Instead they roll up and over them. This action shows up as noise on the straightness traces of roller or ball bearing slides. Roller slides are commonly more noisy when they are first assembled than they are after having been run for a period of time. This is due to the gradual crushing of the particles of dirt by the rollers. Often it is possible to detect periodic short term disturbances in slide straightness which occur either at travel distances equal to one-half of the roller circumference, or at a distance equal to twice the roller spacing. These are caused by bits of contamination which adhere to the roller surface or to the slide or the stationary way surfaces.

Another problem inherent to the use of rolling element ways involves the guidance of the rolling elements. The rollers or balls are usually constrained to move parallel to the slide travel at some predetermined spacing by a retainer. This retainer, especially in the case of rollers, must itself be a device of high accuracy. If the rollers are allowed to place any significant force on the retainer because of skewed pockets or diameter mismatch, the slide will exhibit changes in attitude when its direction of travel is reversed and the forces on the retainers are relieved.

In summary, rolling elements seem to work best on relatively large, heavy slides where the slide weight can be used to increase the preload on the balls or rollers. The rolling elements should be as small as possible without getting into strength of material of material problems, and as numerous as possible. Rollers, if used, should be short, no more than three or four diameters in length.

Non-metallic friction

Non-metallic friction type ways have a place in ultra precise mechanisms. There are several commercially available materials which are Teflon based composites and are intended for use in sliding contact applications. These materials and virgin Teflon itself can be applied to machine slides. If these materials are used, they should be lubricated rather than used dry. Common way oils are the recommended lubricants. Even in the lubricated condition there will be a certain amount of stick-slip which will effect positioning accuracy. Also, at very low speed there occurs a shearing action between the material and the way surface which results in the generation of debris, which will affect the accuracy of motion of the slide. This generation of debris is much reduced when virgin Teflon is used instead of a composite material.

Non-metallic ways would normally be considered for applications where the slide motion is more or less continuous and at moderate speeds during the machining process.

Air hydrostatic bearings

Air hydrostatic bearings are a common choice for ultra precise slides. They are relatively easy to make, have a zero coefficient of static friction, and tend to average the short term imperfections on the way surface. There are disadvantages however.

Air bearings provide almost no damping to the machine system; therefore structural resonant frequencies can become a serious problem. The lowest natural frequency of most slides is a mode where the slide vibrates along the ways with the ball screw or other driving mechanism as the spring. The frequency of this mode often falls within the range rotating machine members, making certain spindle speeds unusable. Here is where efforts to reduce the mass of the slide can really pay off by raising this vibration mode out of the range where spindle speed will excite it.

Vibration can also be a problem in the design of the bearings themselves because, unless care is taken, the bearing will vibrate as soon as it is pressurized. In order to prevent this, do not design bearings with recesses around the inlet orifices unless absolutely necessary. If recesses must be used, they must be as small as possible and even then instability may limit the air pressure which can be used.

Porous bearings are sometimes used in this application both to improve the stability of the air film and to reduce the effects of scratches and local imperfections on the mating surface. Porous bearings however, can exhibit the same instability as the more common orifice controlled bearings; when it occurs it is much more difficult to eliminate.

Particular attention must be paid to the cleanliness of the air delivered to air bearing ways. Water, oil and particulates must be removed to prevent clogging of orifices, porous material, or the film itself. Typically coalescing filters of one to three micron absolute rating are used to achieve the required cleanliness.

The pressure of the air supplied to the bearings must be accurately controlled so that the thickness of the air film remains constant. This requires a pressure regulating valve which can control the pressure to within a tenth of a psi or thereabouts. Less accurate control can cause wandering of the slide which shows up as non-repeatable errors of straightness. Air bearings also should be protected with some mechanism which will prevent the slide from being moved unless the air pressure supplied to the bearings is between some preset limits. This usually means the inclusion of a pressure switch of some sort.

Even though a filter is included which will remove water from the air supplied to the bearing, materials which do not rust are required. The consequences of rust are so serious that no chances can be taken. In addition to this, materials should be selected which will run together without lubrication without welding together or seizing. All air bearings are sometimes made to move without the air pressure applied and here again, it does not pay to take chances.

Oil hydrostatic bearings

Externally pressurized oil hydrostatic bearings are one of the best choices for ultra precise slides. These bearings have a zero static coefficient of friction, they allow damping to be designed into the system to control vibration, and they can be designed to have very high rigidity. There are disadvantages to these bearings however, and they must be reckoned with.

One of the most serious disadvantages is the mess that oil bearings create. Oil seems to ooze from everywhere. There are certain techniques however, which can help eliminate the problem. Design the slide with the idea in mind that the drainage of oil away from the bearing surfaces and back to the reservoir requires large holes and plenty of clearance through passageways. Make the drain gutters larger than seems necessary and remember that capillary action will tend to pull oil into small gaps in dust shields and the like. Try to keep as much plumbing as possible in places where, if leaks occur, the drips will end up in the areas already set aside for drainage. By careful attention to detail and generally conservative design, it is possible to build a slide which does not drip oil onto everything around it.

Hydrostatic bearings, by their very nature, require an outside source of pressure and this usually means an oil pump of some kind. Oil pumps consume power and therefore get warm; in addition, they make the oil warm. There are at least two ways of tackling the problem of temperature control. The first is to use a heat exchanger to maintain the temperature of the oil at a controlled value. The second method is to design the bearings to consume an absolute minimum of power. By designing using low pressure and small clearance with flow control valves for pressure compensation, high stiffness can be achieved without consuming a large amount of power. Two or three watts is all it takes to support a slide weighing several hundred pounds. With that low an input power, temperature control can be achieved by designing a reservoir with a generous surface area.

An advantage of designing around relatively low oil pressure is that the forces exerted on the slide structure by the bearings are lower, and this means less distortion of the structure.

Use oil which has a relatively low viscosity, even though this increases the flow through the bearings and increases the power required. Liquid bearings have a substantial load capaçity due to the relative motion of their surfaces. This effect is unrelated to the hydrostatic bearings but it causes the slide to move away from the way surfaces when it moves. Using a low viscosity oil minimizes this problem.

The oil pressure supplied to the bearings must be carefully controlled, particularly if the ways are not captured but rely upon gravity for their preload. Most pressure control valves do not operate well at the very low flows needed by these bearings. One way around this problem is to servo control a positive displacement pump using a sensitive pressure transducer as the feedback element. A servo amplifier and motor drive the pump at a variable speed so as to maintain fixed pressure to the bearings. By this technique, pressure can be controlled to well within a tenth of a psi.

Cleanliness is as important to the proper operation of oil hydrostatic bearings as it is to air bearings. The internal clearances of the two types of bearings are about the same, and the filters used to keep the fluids clean must be of about the same micron rating. In addition, the internal drilling for oil passageways must be thoroughly cleaned prior to passing oil through the bearing.

An advantage that oil bearings have over air bearings is in vibration control. Damping can be designed into oil bearings by controlling the configuration of the bearing recesses and other aspects of the bearing geometry. In some cases turned mass dampers can be constructed as part of the slide design to eliminate troublesome natural frequencies.

Although oil bearings have a zero coefficient of static friction, it does take some force to shear the oil film and cause the slide to move. This force is proportional to the velocity of the slide and to the area of the ways. Because of this it is possible to control where the center of resistance is and to position it so that it falls directly in line with the center of effort of the slide drive. This means that there will be no change in the attitude of the slide as it reverses its direction of motion.

Designing the way system

After arriving at the configuration of the slide and after selecting the type of bearings to be used, it is time to decide on the configuration of the ways themselves. There are probably as many different types of ways in use today as there are machine designers. Everyone seems to have their own preferred approach however, certain basic rules apply to all designs.

The first question is whether to support the slide with a bearing at each corner or to use only three points of support. This obviously does not always apply to rolling element bearings where the retainers are longer than the slide. It does not usually apply to air bearings which, in order to get adequate load capacity, are usually distributed along the entire length of the slide. For oil bearings with control valves for enhanced rigidity, always use three points because, if the slide behaves as a rigid body, four support points are indeterminate and will result in the slide showing high stiffness at two diagonally opposite corners and low stiffness at the other corners.

Avoid overconstraining the slide. Although some designers have had success with double vee ways or double cylindrical ways, these approaches are ill advised. A single vee or cylinder will control a slide in four degrees of freedom and a simple flat will take care of the fifth without requiring unnecessary precision. Overconstraint leads to high forces which are locked up in the slide and in the ways. These forces cause deflections which are more likely to degrade the precision of the system than they are to improve it.

Design using symmetrical ways if possible. This reduces the chance of yaw errors at slide reversal. Asymmetric ways lead to tradeoffs in the design of the drive system. The drive should be designed to push or pull the slide at both its center of gravity and at its center of resistance. Misalignment with the center of gravity produces pitch and yaw due to acceleration forces; misalignment with the center of resistance produces pitch and yaw due to friction forces. If air bearings are to be used the center of gravity is most important; if oil bearings, then the center of resistance should be favored.

When choosing the configuration of the ways, try to minimize the number of guide surfaces required. Each additional surface requires precision machining and careful control of geometry. Also, when hydrostatic bearings are used, each surface consumes additional lubricant and requires an increase in pump or compressor power. Make the ways somewhat longer than required so that when they are machined, the transient effects caused by the grinding wheel moving onto and off of the surface are confined to an area outside of the travel of the slide. Generally, an inch or two at each end is sufficient for this purpose. If gravity is used to preload a slide with hydrostatic bearings, remember that the bearing supply pressure will have to be carefully controlled to prevent the slide from rising and falling as the pressure fluctuates. Guide on one surface if possible rather than averaging between two opposed surfaces. This can be done by using highly rigid bearings on the guide surface with much less rigid bearings opposing them. The advantage to this is that the geometry required is less precise than if both opposing surfaces act as guides. The best advice is to choose the simplest design which will do the job and avoid over constraining the slide.

All preloaded ways generate forces which are locked up in the slide and way system. These forces distort both the slide and the ways to some degree, and they can affect the straightness of the slide travel if they pass through areas of changing rigidity as the slide moves along the ways. To minimize this distortion, use preload forces which are no larger than necessary. More importantly, design the way support structure to have the same rigidity at all points along the travel of the slide. It is possible to select a configuration of ways which minimizes distortion due to the preloading forces by confining these forces to the smallest possible area of the support structure. These configurations should be given serious consideration during the initial phases of the design process.

Finally, when designing the ways, remember that someone will have to manufacture and build the design. Many otherwise excellent designs are poorly executed from the standpoint of manufacturability and serviceability. If the handling and fixturing of parts is considered during the design process, the end result will be component parts which are more accurately machined. More accurate components will contribute significantly to the accuracy of the finished slide.

Peripheral concerns

In addition to the design of the slide and the ways, there are several other things which must be considered if the accuracy of the finished product is to be maximized. If electrical, air, vacuum, or hydraulic lines must be attached to the slide they must be connected so as to minimize their effect upon the straightness of travel of the slide. In some cases symmetry can help balance the forces generated by the wires and hoses. Keeping the connection low and near the center of the slide can help. Try to eliminate as many connections as possible and keep the others to the smallest size possible.

Limit switches should be of the non-contact variety and they should be mounted externally so that if they fail or need readjustment they can be replaced or moved without disassembling the slide.

Position feedback devices, if used, must be located in a clean, dry area where they will not be exposed to oil or other contaminants, and as close as possible to the line of action of the slide in order to minimize Abbe offset errors.

Way covers should be used to protect the ways from damage by tools or dropped objects and to keep the way surfaces clean. These covers, where possible, should be rigid, one-piece devices. Avoid telescoping way covers because the sliding action of the covers extending or retracting affects the accuracy of the slide motion. Soft, accordian pleated way covers are a second choice because they are hard to keep clean and, after a period of use, they can develop holes which may go undetected until the ways are damaged by a chip or coolant which has worked its way through the holes. This type of cover also exerts a sizable force on the slide as it extends.

Summary

The successful design of ultra precise machine slides requires attention to detail and an unwillingness to accept anything which is not the very best solution to the problem at hand. Inevitably compromises have to be made, but they must be as few in number and as small in effect as humanly possible.