

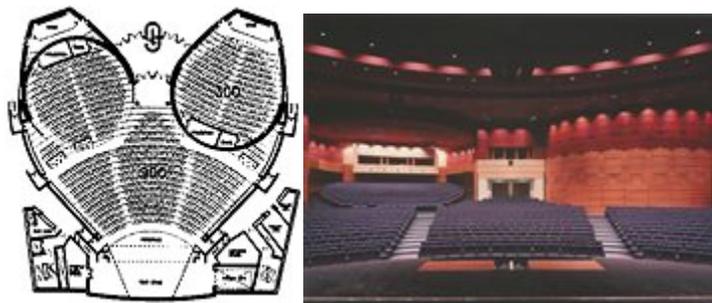
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21M.735 Final Project

### Using a Turntable on a Raked Stage

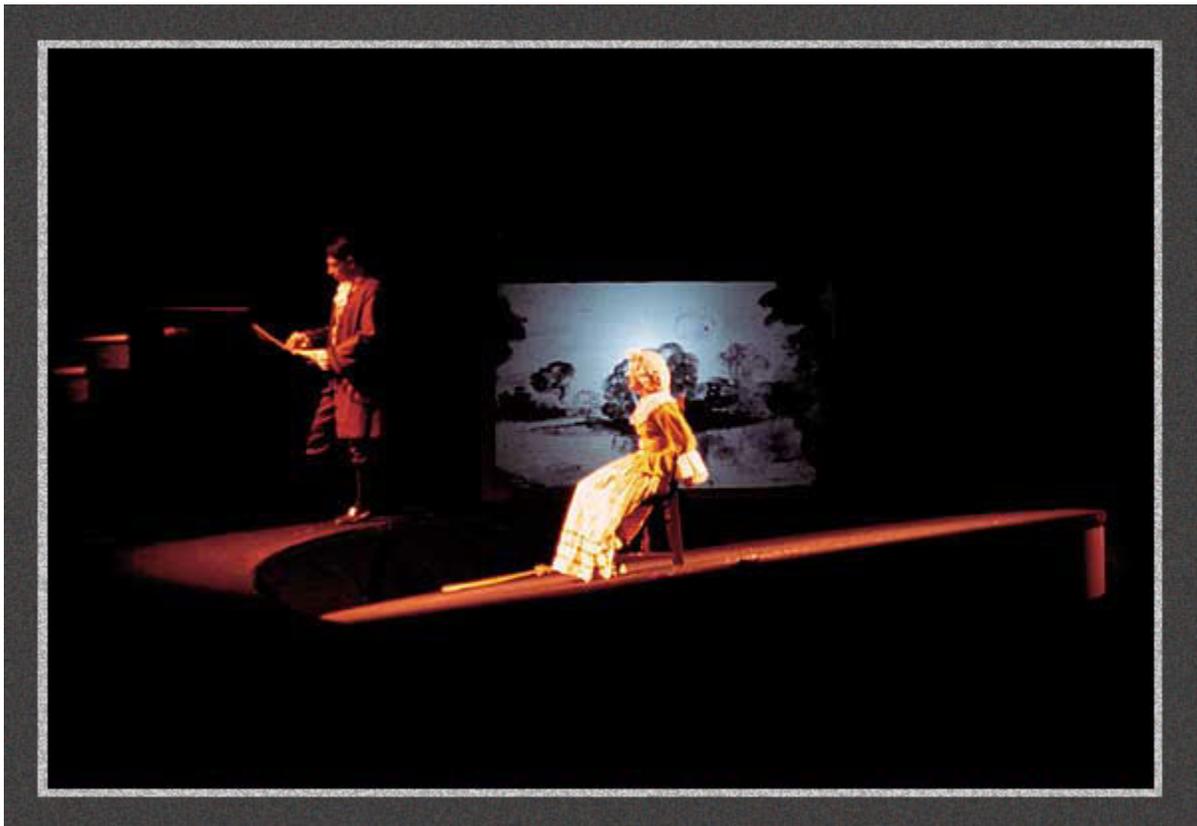
This project will examine some of the implications involved in creating a turntable on a raked stage, and go through a design analysis for an example scenario.

Turntables and raked stages both have long histories in the theater: raking, where the stage floor slopes toward the audience, was used first to increase visibility of the stage. In more modern times, where it is often the audience area itself that is raked, raking is still used as an effect to provide strong division between upstage and down. Turntables, also known as revolves, can vary in size from tiny enough to hold one scenic element, to large enough to span the proscenium and support the entire set. Both still have prominence today, and are fairly common.

What is less common is to find a scenario where the two are combined on the same set: a stage that is raked, and on top of the rake or set flush with it, sits a turn table, with axis of rotation perpendicular to the raked stage surface. In fact, a search for “raked AND turntable” turned up examples where the top of the turntable was raked, but the axis of rotation remained vertical.



This is a schematic and a picture of a theater in Edinburgh, Scotland, which features two massive turntables with raked tops, in this case holding seats. By rotating the seating sections, the theater can become one massive conglomerate, or one medium sized auditorium and two mini auditoriums. While innovative, this application is not one where the turntable itself is raked; rather, the structure on top is raked.

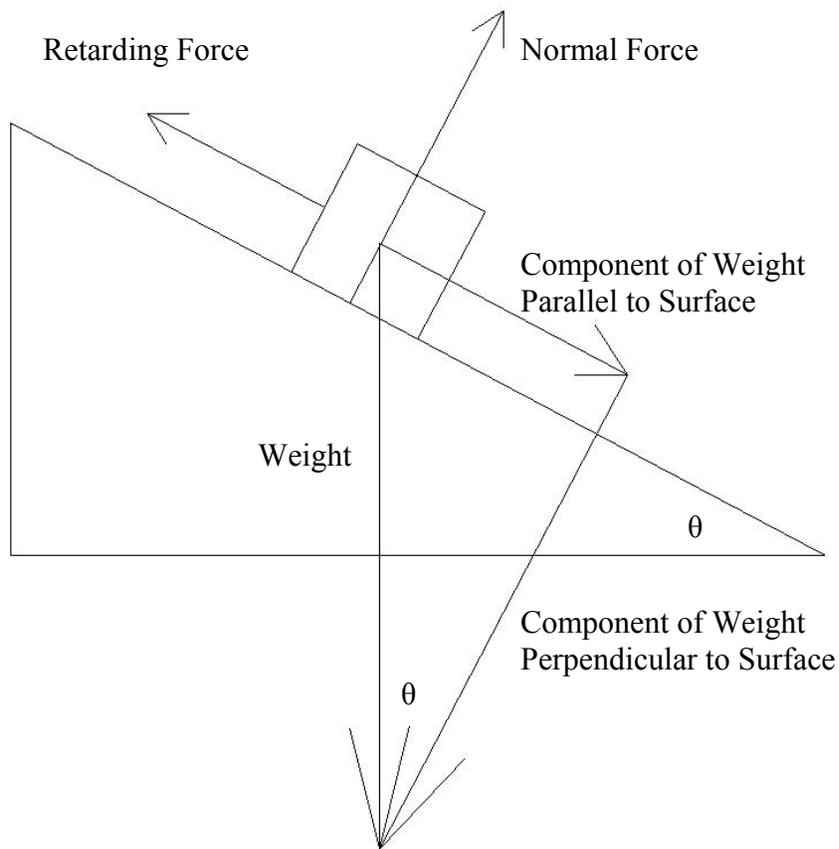


This picture is from a production of Vinegar Tom at California State University. Here too, based on the fact that turntable is much below the stage on the left side of the photograph and much above it on the right, the bottom of the turntable is horizontal and the axis of rotation is vertical.

The difficulty in actually constructing a raked turntable comes from the fact that the support mechanisms must have much greater strength. This in turn is a result of the

fact that the turntable is trying to fall off the stage into the orchestra pit, rather than sit calmly when not touched as it does on a flat stage.

Just like any other object that can slide on a raked stage, the turntable has a tendency to slide down the incline. A very general diagram of the situation appears below:



There are three main forces acting on the turntable, represented above as the block, on the inclined plane of the rake stage, which is at an angle  $\theta$  above the horizontal. The first is the weight of the block, which, due to gravity, pulls straight downwards. The second is the normal force of the stage supporting the turntable, perpendicular to the

stage surface. The third is the retarding forces that prevent the turntable from slipping down the slope. Their actual content will be discussed later.

The weight can be resolved into two normal components, one in line with the normal force, one in line with the retarding force. Because the turntable is currently in equilibrium, the vector sum of the forces acting on it must be zero. Thus, the component of the weight normal to the surface is balanced by the structural soundness and resulting normal force of the stage, in the same way that a regular stage keeps the turntable from falling through. The major difference is now the stage or fixtures attached to it must also provide the retarding force necessary to keep the turntable from coasting down toward the audience.

To give an idea of the magnitude of the force involved, for a rake of  $15^\circ$ , the percentage of the total weight of the turntable tending to pull the turntable down the slope is  $100 \cdot \sin(15^\circ) = 25\%$ . To further try to conceptualize, imagine trying to push a cart filled with enough weight to balance the weight of the turntable plus actors and scenery up the raked stage, or even just holding it from falling down. That same amount of force is what the stage must apply.

Another major issue at stake is actually driving the turntable. Whereas beforehand, the drive mechanism merely had to overcome the static and dynamic friction inherent in the system's moving parts, any off-center net loading of the platform, such as actors or set pieces not arranged precisely about the center of the platform, must be actually lifted up or carried down in a vertical displacement, which, because of the change in potential energy the load experiences, requires more work on the part of the drive system.

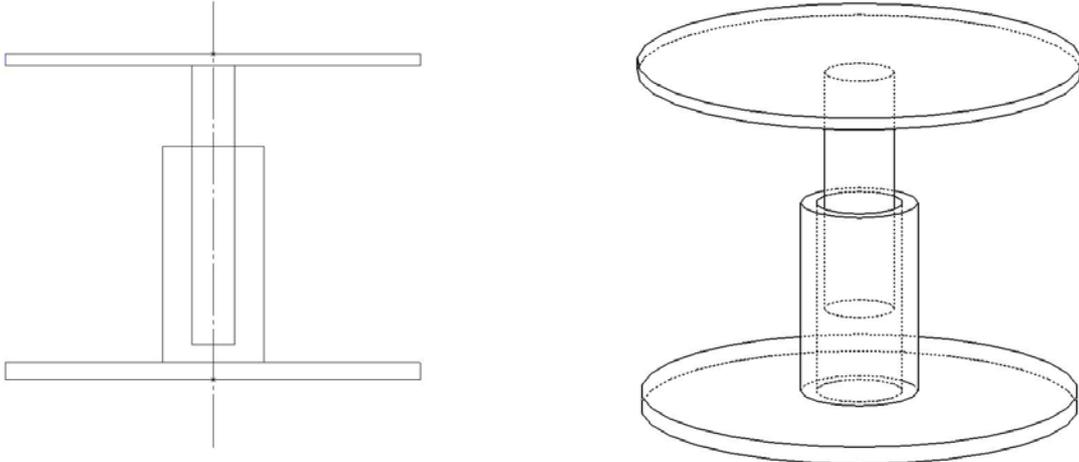
Friction is inversely proportional to the direction of motion, which means that for the flat case, the drive system is always fighting to overcome the friction as it moves the turntable, but luckily, when the turntable is at rest, the force of friction is also at rest. During the full rotation in the flat case, there is no alteration of load. In the raked case, again assuming off-center loading, none of these are true. Even if the turntable stops moving, it may need to have an at-rest torque applied to keep the heaviest side of the turntable from pivoting to the bottom, like a bicycle wheel with a weight on one side. As the load is moved upwards and away from its perihelion, there will be a very large force against the motion. When the load is moving down the slope, the opposite will be true, and the drive system will be fighting to slow the turntable down from going too fast.

For these reasons, the drive system must be both very strong and very resistant to force disturbances at the output. It must also have a very good adhesion to the turntable itself: Merely wrapping a cable around once and relying on the capstan effect may not be enough gripping power to maintain control.

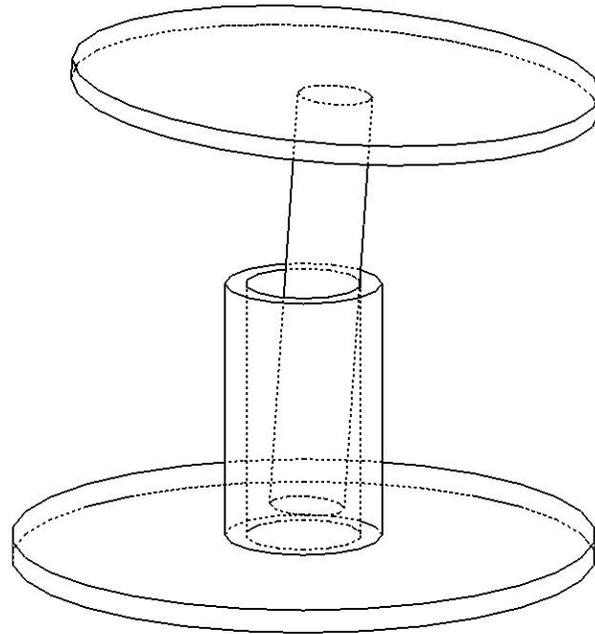
The major issue remains: how to resist the forces that would otherwise pull the turntable down the stage, and it is there that I shall devote the rest of my attention.

The turntable in raked application can be fabricated along traditional guidelines, either stressed-skin or joist/platform construction. The underside castering can also be done as usual, either attaching the casters to the platform itself or the floor. The major difference must come in how the transverse weight is supported. Since the turntable must rotate, it can't be simply bolted to the floor in the same way a box sliding down the stage could be. Rather, the supports must be able to transmit the retarding force through some sort of bearing that allows the turntable to keep rotating.

The first idea is to transmit the retarding force through the same pivot that is used in flat applications, a simple version of which is pictured below in cross section and in isometric view:



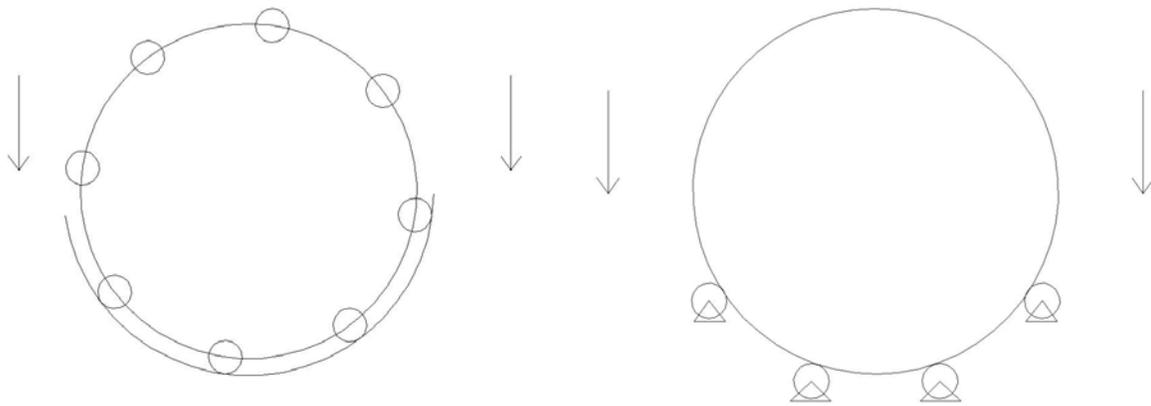
The basic idea is that two tubes slip one inside the other, allowing translational motion to be constrained while rotation is still free. The top plate would be bolted to the turntable, and the bottom lagged into the floor. However, if the same mechanism was attempted to be applied to the raked case, a fundamental difference would occur. Now, there would be a large force acting in the plane of the top plate; that force would be the retarding force of the turntable. The pivot would likely deform like this, as seen from the point of view of the raked stage:



Now, instead of being able to move freely, the pivot is likely to bind in its movement, with the entirety of the force being applied at two points, causing immense friction at those two small places, in addition to deformation of the material which would enhance the friction. Also, since these plates are fairly small relative to the forces involved, it might be possible that they would rip out of either the turntable or off the stage, causing catastrophic failure. Thus this design is not sufficient.

Proceeding from there, there are two avenues available: To attempt to reinforce the pivot somehow, or to attempt to support the turntable elsewhere.

The latter idea would have to be casters between the downstage edge of the turntable and some other rigid surface, either attached to the turntable itself or attached to the stage floor:



In both cases, the arrows indicate the direction of decreasing slope. There are a few drawbacks that become apparent with both variations of this method. The primary one is that the casters and the extent of the circular surface they bear upon must be completely concentric. This means that either the semi-circle attached to the floor or the turntable itself must have a nearly perfect circle with a few inches depth for the casters to bear upon, and the casters must all be aligned the same distance from the center of the turntable to properly bear on the circular section. If either component is out of line, then the same transverse stress on the pivot will apply, and undesirable outcome.

The second drawback is that, at least for the left-hand suggestion, the turntable has casters coming off all over the circumference. With a turntable set into the raked stage so the surface was flush, this would not be as much of a problem, but for a raised turntable, both the casters and the support for the casters would be visible, potentially detracting or distracting from the audience's enjoyment of the show.

Thus the better option in this case is to attempt to reinforce the pivot point to be able to bear the brunt of the force. This has the advantage of being discreet, if it can be of sufficiently low profile to be concealed under the turntable, and less likely to misalign, given the smaller number of precisely toleranced components.

The first thing to do is to find a bearing that is designed for this general application, and then see if it can be fit to the specific instance at hand.

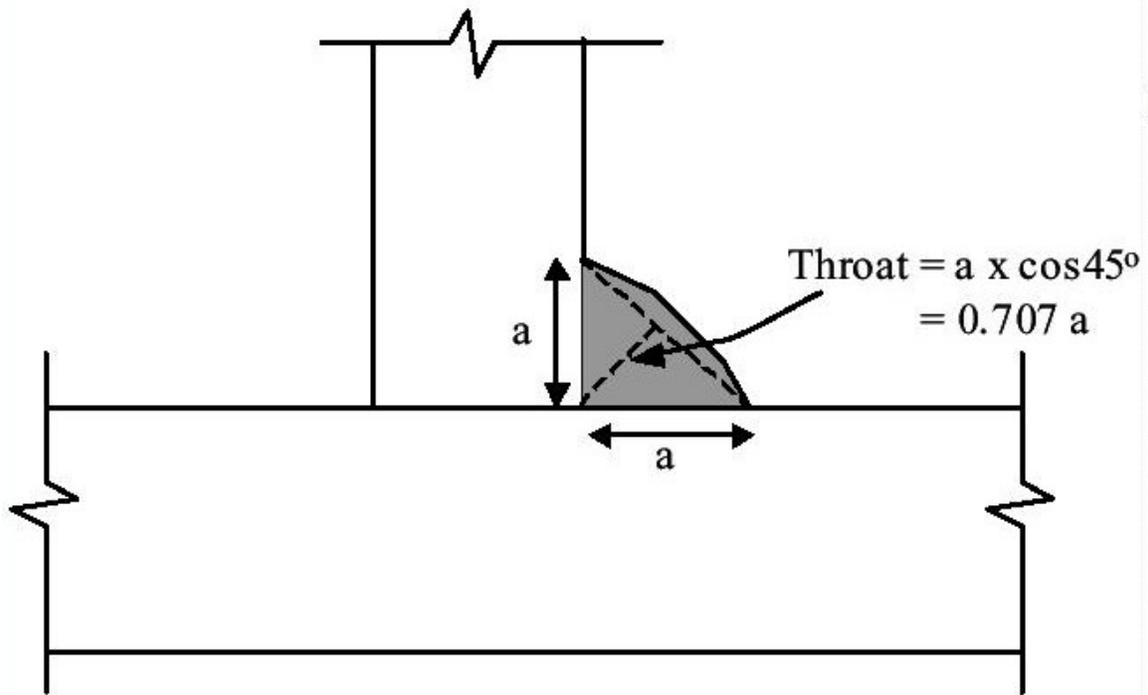
Research on bearings reveals that there are bearings known as “thrust bearings” which are used to transmit axial force along a rotating shaft, such as for an airplane engine, where the propeller is pulling the shaft which is pulling the motor, which is pulling the airplane itself. However, these are unsuitable for radial loads, which is what are at work in the raked turntable pivot.

The answer is pillow blocks. Pillow blocks are designed to provide the adequate rotary freedom of the shaft while supporting the shaft for radial loads. A picture of a pillow block appears below.

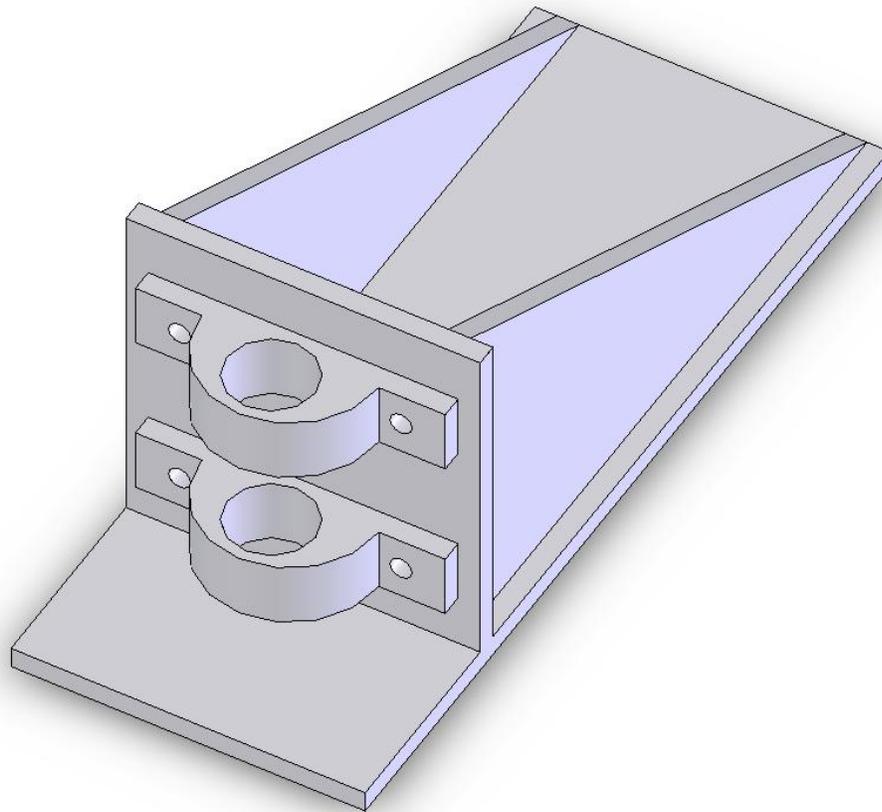


It is not sufficient to have merely one of these on the shaft, as that wouldn't properly confine the motion at high loading (think of grabbing a broomstick with only one hand in the middle and trying to resist someone pivoting it at the top). Thus, two will be employed to fixture the shaft (grab the same broomstick with two hands separated by a short distance, and try to see how easy it is to rotate now).

Now that the correct component has been located, it is necessary to properly interface it with the theatrical application, which is to say, it has to be bolted to the floor in the right way. To do so, I would suggest the welding together of a four-piece structure out of 1/4" steel. For the theatrical shops with the capacity for welding, welding, in conjunction with the steel, can provide a good deal of strength. A cross-section of the weld is shown below:



The strength of the weld to resist shearing force is the product of  $\frac{3}{4}$  times half the square root of two times the distance "a" marked above times the length of the weld, times the shear strength of the weld material, often comparable to the shear strength of the steel. The final part appear below:



As can be seen, this structure combines four pieces of sheet steel in creating a sufficient support for the pillow blocks. At just 4 inches high, tapering to  $\frac{1}{4}$ " , it is fairly low profile. The structure is designed to be arranged with the triangular blocks pointing down the slope of the stage. This will transmit the force from the turntable, which will net in a forcing pushing normally to the vertical piece, down to the floor piece, which will be sufficiently well attached to the stage floor with lag bolts. There is a large area with which to attach bolts, both in front and behind the vertical piece. The one worry for structural stability would be buckling of the triangular pieces, but it is likely that with sufficient design preparation and calculations, the exact dimensions could be set to match the expected loading parameters.

In conclusion, I designed the structure shown above to fulfill the role of providing adequate support to a turntable on a raked stage, thus further widening the number of tools and tricks at the theatrical designer's fingertips. Further work could look into the various drive options for the turntable.

Schematic drawings of the mechanism appear on the next and last page.