Torque amplifiers in Meccano

Tim Robinson

I will discuss here experiences gained over a couple of decades of on and off work to construct a Differential Analyser in Meccano, capable of an accuracy approaching that of some of the original machines of the 1930's. The most fundamental problem to be overcome is that of providing adequate torque amplifiers. This is a challenge indeed within the confines of the Meccano system, for while it is very easy to build a demonstration model, amplifiers which will perform reliably for hours, and with the sensitivity and gain required for a serious Differential Analyser are another story.

Although the concept of the Differential Analyser dates back to the work of the Thompson (Lord Kelvin) and his brother [1], the first actual machine was not constructed until Vannevar Bush at MIT together with Nieman at the Bethlehem Steel Corporation created the first practical torque amplifier. An excellent description of this machine is provided in [2]. A brief description, including pictures also appeared in two articles the June 1934 Meccano Magazine [3], [4]. Interestingly, in a follow on second generation machine, Bush abandoned torque amplifiers in favor of an electromechanical servo system [5], although the primary motivation was to allow the tedious mechanical reconfiguration of the machine between problems to be accomplished by electrical switching instead.

An introduction to the torque amplifier problem in Meccano, and an excellent demonstration model, can be found in Michael Adler's Torque Amplifier Modelplan on the ISM website [6] which also includes references to a number of other articles on Meccano torque amplifiers.

The simplest design consists of a pair of contra-rotating drums mounted on collinear input and output shafts. A pair of cords or belts wrapped around the drums connect two arms mounted on the input shaft and output shaft. Here we run straight into a limitation of the Meccano system, in that we do not have available a concentric shafting system. Since the objective is to amplify a minute input torque, we need to eliminate any spurious sources of torque which may otherwise get applied to the input shaft. Consequently what is really needed is a concentric shaft at the input with the drum running on a stationary sleeve around the input shaft to protect it from friction from the drum. While there is a similar spurious torque in the opposite direction being applied to the output shaft by the second drum, this in no way compensates, since the gain of the amplifier means the friction from one drum is amplified while that from the other is not. In the Differential Analyser application, the presence of this torque on the input shaft typically results in a steady creep of the integrator wheel even when it is in contact with the integrator disk, and certainly if it is lifted clear.

A partial solution to this is to apply a compensating torque to the input. This can be done by having another rotating element on the input shaft, turning in the opposite direction to the drum, and held in light contact by a compression spring to a collar on the shaft. However, while this can be adjusted to provide a fairly accurate balance in the short term, it is not be effective over longer periods as the level of friction between the elements varies over time.

The problem of the creeping integrator wheel brings us to another major problem area for Meccano construction of the amplifier – vibration. Any vibration present in the amplifier will be transmitted along the input shaft to the integrator wheel. The integrator wheel is in relatively light contact with the disc of the integrator. Contact must be light here as otherwise lateral motion of the disc is impeded, introducing a new set of systematic inaccuracies, and small amounts of vibration dramatically reduce the friction available at the wheel to disc interface. In effect the wheel is bouncing up and down on the disk and in an extreme case spending some of its time not really in contact at all. Eliminating vibration is mainly a matter of balancing rotating elements, eliminating all play in bearings, and finding dead straight axle rods.

It is instructive to take a diversion here to consider some absolute numbers for the input and output torques involved. Even with careful construction, rigid frames, accurately aligned bearings etc, Meccano does not provide us with precision engineering, so losses through a complex transmission rapidly mount up as anyone who has struggled to stop grub screws slipping on axles will know. Thus at the output of the amplifier we want as much torque as possible, within the limits of what we can reliably transmit through normal bosses to drive the rest of the machine. This number is certainly in excess of 2 Kg cm (in Bush's original machine, the amplifiers could deliver up to 1 lb ft [2]). In contrast, the torque available at the integrator wheel may well be of the order of only 1 gm cm or less, indicating that a gain in the amplifier of at least 1000 is required. Intuitively, one might expect that the error introduced at the integrator wheel would be zero so long as the torque is less than that required to make the wheel visibly slip. However, careful measurements on the original machines [2] in fact showed that there is an error before that point, which increases linearly in direct proportion to the amount of torque being taken from the wheel. In order to minimize this error we therefore would like to have amplifiers with the highest possible gain and with the lowest possible amount of spurious torque being applied at the input.

A major improvement is possible by mounting both drums on the output shaft and running the input shaft parallel to this instead of collinear. This arrangement is used in the demonstration model in [4]. In this arrangement, the input arm consists of a gear wheel mounted freely on the output shaft and driven directly from a second gear wheel on the parallel input shaft. Now we have essentially eliminated the spurious torque on the input shaft and any imbalance in the elements running on the output shaft will be reduced by the gain of the amplifier when considered reflected back to the input. In fact with this design and careful construction, it is possible to have both input and output shafts unconnected externally and there should be no creep of the input at all.

Now back the question of gain. The gain of the amplifier depends on a number of factors, in particular the coefficient of friction between the belts and the drum, and on the number of turns the belts make round the drums. It can be shown theoretically that under ideal conditions, the gain should increase exponentially with the number of turns. So why can we then not get any level of gain desired, just by wrapping the belts around the drums enough times? Unfortunately, once more we find that Meccano does not provide us with the theoretically ideal conditions, nor does the real world provide us with the "light inextensible string" of high school physics. As the number of turns increases, any unwanted friction between the belts and the drums will be amplified. This may come for example simply from the weight of the belt laying against the drum or from imperfections in the drum surface. There is a practical limit somewhere between two and three turns. Beyond this, even with no input present the belts will tighten on the drums with each trying to drive the output in the opposite direction. While these effects may cancel, huge forces can be involved, generating heat but doing no useful work. In an extreme case parts will bend and the amplifier will destroy itself, depending on the capabilities of the drive motor. This limit means that for the performance level needed for better than just a demonstration level Differential Analyser, a two-stage amplifier is more practical. More on this below.

This brings us to the choice of materials for the drums and belts. Within the standard Meccano system our choices are somewhat limited. Possible circular parts for the drums would seem to be limited to flanged wheels, wheel flanges, and boiler ends. The flanged wheels are a little small, and because of the non-standard spacing of the holes rather difficult to attach to other parts to provide the drive. Most examples of the flanged wheels run too far from true to be good for this also, but an ingenious design by John Yewen described by Allan Partridge [7] did use these in an inside out arrangement in which the drums were mounted rigidly on contra-rotating shafts with both the input and output assemblies turning freely on these. Unfortunately, while this solves the drive problem, it still leaves the issue of friction between the input and the drum shaft.

Wheel flanges are a little narrow, and they are slightly tapered which can case the belt to drift to one side when tightened. They can be used though, trapped between faceplates, and with a 6" driving band around to fill the gap created between the curve of the flange and the faceplate to prevent the belt getting trapped there. However, better results are generally possible using boiler ends, and especially the original 1930's type, as these have no holes in the periphery. The challenge with these is created by the domed end, which makes it hard to mount them to a drive gear/sprocket and have them run true. In the design described in [6] they are trapped between a pair of wheel flanges and pressing the open end of the boiler end against the flat surface of one of the wheel flanges provides the alignment.

In another arrangement, which I prefer, a 2" sprocket is fitted inside the boiler end and this assembly is then clamped to a 3" sprocket to provide the drive, with a 1" rubber ring between the boiler end and the larger sprocket. Four bolts can be tightened and adjusted to get this running absolutely true and then finally locknutted since the compressibility of the rubber ring means they cannot be tightened down hard.

The drum surface must be absolutely smooth, as any irregularity will result in erratic operation. This means removing the paint (if any) from the surface and then polishing the metal to a really smooth finish. This can be done by running the drums under power but without any input/output arms in place, using successively finer grades of silicon carbide paper down to 1500 grit, then a finally polishing with a metal polish such as Brasso. This leaves a mirror finish. It is essential to remove all residues and to make sure no oil subsequently gets on these surfaces.

In the arrangement just described there are no raised edges to the drums. While this should not be necessary in operation for a carefully set up unit, it makes installing and adjusting the belts in the first place a very challenging exercise. So to avoid this problem, slip a pair of 6" driving bands on each boiler end to provide edges. If necessary a couple of drops of superglue will hold these in place during handling, so long as this is not allowed to encroach on the surface the belts will actually touch.

Be careful in the selection of the axle used as the output shaft. It must of course be dead straight, but if possible select a rod which is nickel plated or made of bare steel. The modern French rods are plated with a very soft zinc coating. In operation, the heavy load presented by the drums will cause this surface to wear rapidly, causing a build up of metal in the lubricant, and after an hour or two of operation lead to the drum seizing on the shaft.

Now to the belts themselves. Most Meccano cords are not really adequate, though the nylon cord provided with the Clock kits might just be. This is certainly an area where the non-purist will want to step outside the system. A woven cord is much better than a twisted one, because it eliminates a bias that will otherwise cause the belt to move sideways on the drum. In selecting the cord, the important considerations are strength, which will determine how much it will stretch under load, flexibility, and stability under change of temperature. This latter is important because, in operation under load, the friction on the drum will result in heating. Contrary to intuition, most cords on heating actually get shorter not longer, with the unfortunate side effect that positive feedback sets in. The tighter the belt is, the more heating, which causes it to contract and tighten further. Considering the desired output torque a fairly substantial cord is called for, however considering the available input torque we want something very light and flexible so as to respond smoothly to the input. The choice is a compromise, though as will be discussed shortly, the ultimate solution for the Differential Analyser application is a two-stage design, and a different choice of belt is then possible for each of the stages.

A readily available material is the Dracon cord used by serious kite flyers. It is available in a range of breaking strains. In a two-stage amplifier the 20lb grade is a good choice for the first stage and the 75lb grade for the second stage. There is almost no stretch with the loads involved, but it does still shrink very slightly on heating so it is necessary to provide a little slack in the belts under starting conditions. 3M Fisherman's fly line backing is another readily available material with very similar characteristics.

Again contrary to intuition, it can be better to provide lubrication for the belts. The motivation is that any loss in gain caused by the lower coefficient of friction between the belt and the drum can be compensated for by an increased number of turns, but the resulting operation will be smoother and more consistent. However, choice of lubricant is critical – viscous materials such as oils should be avoided. In the original Differential Analysers, belts were lubricated with dry graphite. A modern equivalent is readily available in the form of a suspension of graphite in alcohol (which of course rapidly evaporates away) and is easy to apply.

We have talked of the need for a two-stage design to achieve the gain desired in the Differential Analyser. The simplest way to achieve this is to make two amplifiers and literally just connect the output of the first to the input of the second. This can have the disadvantage of being rather bulky. However, for those looking for more of a challenge, there is a much more compact way which uses just a single pair of rotating drums but with two separate belts on each. Suppose we were simply to double the number of turns of the belts. We know this will not work, as they would simply bind up - but, if we now find the mid-point of each belt and effectively connect these together via a third intermediate arm we can create the two-stage unit in almost the same space as the original one stage unit.

How to do this, given the lack in the Meccano system of concentric shafting? We can rigidly attach the two output arms to the output shaft. We can carry in input arms on a gear running on this shaft, but for the intermediate arm, we need to connect the belts on the two drums one either side of the input gear. It turns out there is a way to do this, based on the observation that while input, intermediate, and output arms all need to be able to rotate relative to each other, they only need to do so through a very small angle once the belts are correctly adjusted. Thus if we make the input arm assembly from a 2 ½" gear (bolted back to back with a faceplate with spacing washers) to remove some of the slop in the boss, it is possible to make the intermediate arm in two pieces, one either side of the input arm and connect them together through the slots in the gear. This can be done this using 1" x ½" double brackets connecting strips as the intermediate arms, but a better solution is to make the intermediate arms from a pair of face plates connected by four reversed angle brackets through the slots. Careful spacing with washers is needed and lots of fine adjustment to ensure the maximum amount of relative motion between the input and intermediate arms is preserved. Although much harder to assemble, this results in a much more rigid structure for the intermediate arm, with minimal slop in the bearings.

With this two-stage design a gain in excess of 10000 is possible. In fact given the limited output torque which Meccano shafts and bosses are capable of handling, the gain is large enough that it is almost impossible to determine the actual gain, as the required input torque to is so close to zero as to be very hard to determine. This brings us to another subtlety. Once we have eliminated all spurious torque from the input shaft, and increased the gain so far, any imbalance in the input shaft and arms will be noticeable. The input side must be carefully balanced so that it will sit in any position without a tendency to drift round under gravity from the imbalance.

In Bush's original Differential Analyser [2] the input shaft carrying the integrator wheel was mounted in a jeweled bearing at the integrator disk end, and with the collinear design of the amplifiers, the bearing at the other end was actually the output shaft. This arrangement minimized friction on the input shaft. Meccano does not provide us with jeweled bearings alas, and the lack of concentric shafts has led to the parallel input/output shaft arrangement so that the option of journaling the other end directly on the output shaft is also not possible either. It is however perfectly possible in Meccano, for this application, to create essentially friction free bearings for the input shaft. Having done this, giving the input shaft a light spin will result in the whole assembly continuing to rotate for tens of seconds with the output fully loaded, before finally coming back to rest.

To get the effect of friction free bearings we simply have to arrange for the input shaft to be carried in couplings which are driven by the output of the amplifier, at exactly the same rate as the input shaft is turning. Thus, after the very minimal relative motion between input and output shafts required to tighten one or other belt on the drums, there is no friction at all.

Bush in [2] describes a problem where with very high gain, an instability occurred resulting in high frequency oscillations that in extreme cases caused damage to the amplifier. In analogy with electrical amplifiers, a damping arrangement was added to absorb this oscillatory energy before it could build up. This problem has not yet showed up in the Meccano amplifiers, despite the close coupling between output and input effectively provided by the zero friction bearings, but if it did, a similar solution could be adopted to address it, namely adding a flywheel frictionally coupled to the output shaft.

References:

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