CHAPTER 4

The Mechanics of Intermittent Motion

A SPRING-DRIVEN RATCHET

The Problems of Intermittent Motion Mechanisms

Now that we are experts on graphical and elastic body mechanics, let us take a closer look at a special topic—intermittent motion devices.

It would be nice if all intermittent motion mechanisms were as easy to analyze as a "block-on-the-table" or the "finger ratchet," studied earlier. Unfortunately, however, this is rarely the case. In most machines, the driving and driven linkages are considerably stiffer than fingers. Drive velocities are high, and contact times between parts can be very short and extremely difficult to measure. The result: impact, vibration, chatter, surprisingly high contact forces, large energy losses, instability in the machine, and other horrors. Let us take a look at an actual situation.

Spring-driven Ratchet Mechanism

Figure 4–1 shows progressive stages of a ratchet mechanism in operation and corresponding plots of the net torque on the ratchet wheel as a function of time during a single drive cycle. In the first stage (A), only the drive cam is in motion and the net torque on the wheel is zero. In the second stage (B), the cam has released the arm and the drive spring has moved the arm forward to contact the wheel. All the energy which is stored in the arm during this pre-travel is now dumped rapidly into the wheel and into the wheel bearing. The arm produces a very high force on the wheel for a short period of time. This creates drive torque and a bearing reaction force F_B, which, in turn, produces a friction force F_b. This blow inevitably causes the wheel to jump ahead of the arm so that, for a brief instant, the force exerted by the arm on the wheel disappears.

By the third stage (C), however, the arm (still driven by its spring) has caught up with the wheel (because in the meantime the wheel has been slowed by its load and also by bearing friction) and the arm has delivered another, lesser blow to the wheel. The wheel has jumped ahead again, the arm has caught it again, and struck it a third and a fourth time. Following the fourth collision, the arm and the wheel finally travel along together so that the arm exerts a fairly constant force on the wheel (we are assuming a drive spring with a fairly flat rate). The force levels and times associated with each blow are different than those associated with each previous blow, in general, becoming lesser as the two parts get together. There is some opinion that a "typical" machine situation involves about five separate impacts, each time that two links collide. Theoretically, there are an infinite number of separate impacts in each collision, but our old friend "energy loss" does make it possible for the two parts eventually to get together.

In the fourth stage (D), a so-called non-overthrow tooth on the ratchet arm has engaged the inner row of teeth on the ratchet wheel, exerting a sudden, and very sharp, stopping force on the wheel (and producing bearing reactions as before). The net torque

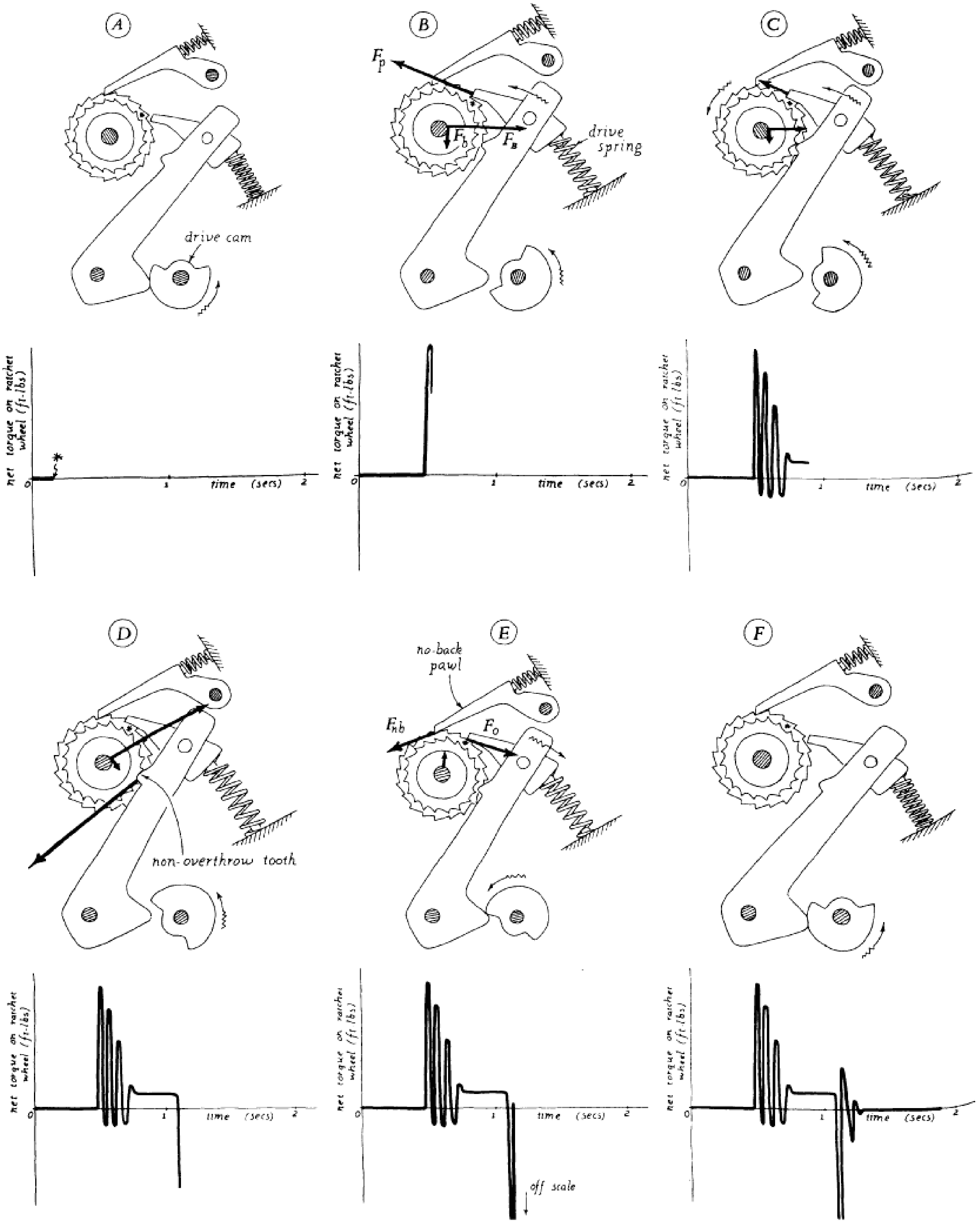

Fig. 4–1. Progressive stages of a ratchet mechanism in operation showing step-by-step development of the torque-versus-time curve for this impacting device.

is negative now and the wheel comes to a stop. The no-back pawl prevents significant rebound but this stop, just as the drive impact, would consist of several short, sharp blows rather than one long one.

As in the simple case of the finger ratchet studied earlier, the positive area under the torque–time curve must be cancelled by an equal negative area if the wheel is to be brought to a complete stop. A little reflection will show that the time required to stop, in this situation, must be considerably shorter than the drive time. In an actual machine the drive time might be a second or more, as shown on the graph, and the stopping time, a small fraction of a second. For the curves to generate equal positive and negative areas, therefore, the stopping torque must be very large, as shown in curve (E).

In stage (E), the ratchet arm has started to retract, driven by the drive cam. The arm, in this condition, exerts a negative drag on the ratchet wheel, but this drag is counteracted by an equal and opposite reaction from the holding pawl, thus the net torque on the wheel is zero and the wheel remains at rest. In stage (F), the net torque on the wheel is still zero. The arm is ready to pick up and drive the next tooth of the wheel.

Calculations—Spring-driven Ratchet

For a real understanding of the ratchet mechanisms, acceleration; velocity; and displacement curves for the wheel as a function of time should be drawn. To draw accurate curves, however, values must be put on the torque curve just sketched in. To do this, the maximum torques, impact and motion times, etc., must be known.

Obviously, these values will be extremely difficult to obtain. Start, perhaps, by drawing a curve of the torque on the drive arm as a function of time. We now have a pretty good understanding of the influence of the drive spring on the arm; since we design the spring (and therefore know just how much force it can produce), and since the spring operates for a fairly long and easily measured time. We know, therefore, what the momentum of the drive arm is when it contacts the ratchet wheel, and can use this to estimate the approximate magnitude of the impact forces when it encounters a stop; similar to the situation illustrated in Figs. 3–1, 3–4, and 3–5.

But the wheel is not a stop. It is free to move and, in fact, is intended to move under the influence of the blow exerted on it by the drive arm. As a result, the arm will lose some, but not all, of its energy when it strikes the wheel—some of this energy going into useful work to drive the wheel; some being lost in bearing and internal friction. The arm will then gain more energy from its drive spring before striking the wheel a second time; and will then let loose a second bundle of energy. It is doubtful that there is a man alive who could calculate these energy losses and transfers.

If the time involved in the multiple impacts was known, on the other hand, impact forces could presumably be computed since we know that the area under the stopping portion of the torque curve must cancel the area under the drive portion of the curve. But again, we hit a snag. We could estimate the time involved in a total collision process, but to measure peak forces, the time for each and every one of the four or five little separate impacts that actually occur during one collision must be known.

Of course, if we could experimentally measure or estimate the maximum forces involved impact times could then be estimated, but this is very difficult also. Impact specialists tell us that the forces generated at the surfaces of colliding bodies are not transmitted equally to all other parts of the body; because we are dealing with elastic bodies, not rigid bodies. What happens is that stress waves move through the body, reflect from bearings or free surfaces, return toward the source of impact, magnifying or cancelling subsequent stress waves (from other individual impacts) that have been generated in the meantime and are themselves surging through the body. This situation makes it virtually impossible to measure impact force levels, even if strain gages were mounted on the colliding bodies.

In fact, there appears to be little that can be done to put actual values on the graph of torque as a function of time which has been drawn for this simple ratchet situation. Mathematically inclined designers are in the same boat, however. They can write equations for this situation and can produce numerical answers, but only by *assuming* impact times or maximum force durations, or spring rates, etc., for the colliding bodies. We can do this too. If you are designing the ratchet, you will know what its inertia is and how stiff the drive and pawl springs are. If you assume that each impact involves a force–time relationship that is sinusoidal (remember the quasi-static model), and that total time duration is on the order of magnitude of a few milliseconds (a good assumption in many machines), also that

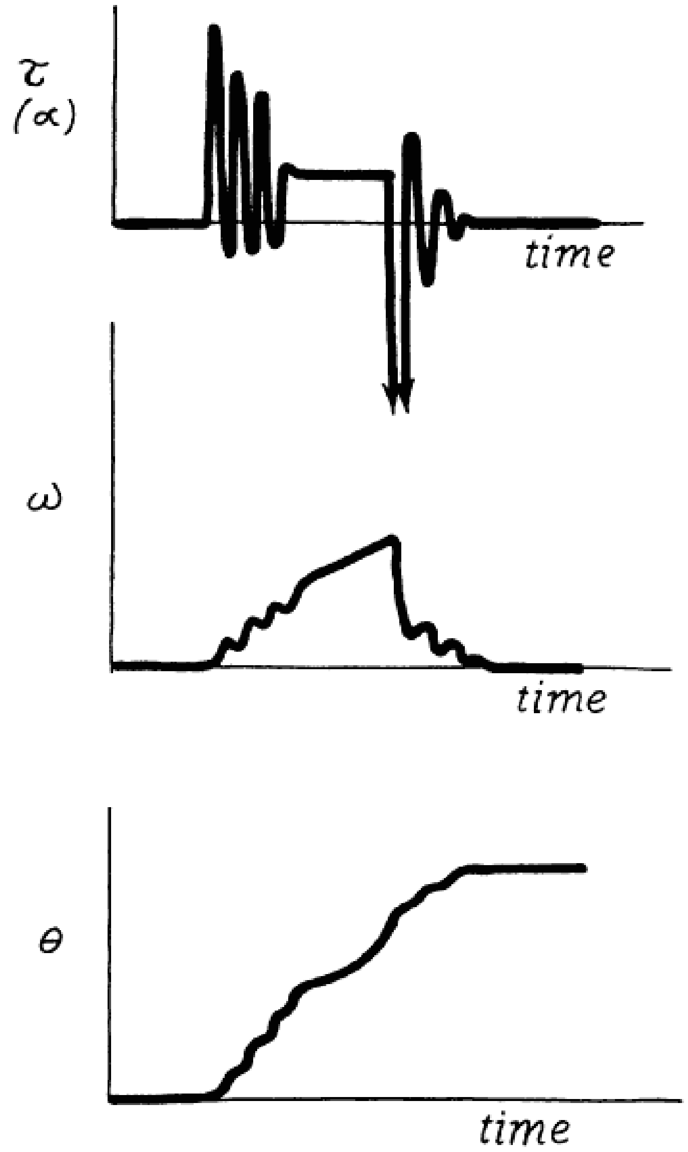

Fig. 4–2. Complete motion curves for the ratchet mechanism of Fig. 4–1.

there will be approximately four or five impacts during each collision, you will be able to rough-in a torque–time curve that is as good an approximation to the actual as the world's finest "calculator" could achieve.

Using graphical techniques we will now approximate the acceleration, velocity, and displacement curves for the ratchet wheel as well. The resulting curves are shown in Fig. 4–2.

THE PROBLEM OF FORCE MAGNIFICATION

We have run into a serious problem in trying to calculate the exact force, acceleration, velocity, and displacements of an intermittent motion device when collisions are involved. The analysis, however, has revealed other problem areas that are perhaps more important to us as machine designers than the purely theoretical problem of being able to put exact numbers on the various functions involved. For example, we have again exposed the problem of force magnification first considered in Chapter 3. Even though we cannot calculate exactly what the peak impact forces are, we can see that they can be many, many times greater than the drive forces which we have thoughtfully provided for our machines—structures and linkages intended to survive only under drive-force levels would fail very rapidly in many intermittent motion mechanisms. Increased stiffness and strength is most easily accomplished by an increase in the mass of the parts and structure involved. But we have seen that increases in mass tend to increase force levels during impact, defeating the purpose of the mass increase. It is necessary, therefore, to do everything possible to provide increased strength with a minimum increase in mass. Machine design experience shows that this can be done in most situations so that the various parts are capable of withstanding the forces involved.

But the problem goes beyond that of designing parts that are strong enough not to break down if subjected to operating forces. Usually the concern is about the cost of the machines; and infinite strength and stiffness cost money, especially if mass must be minimized. Furthermore, even if machine members are strong enough not to fail catastrophically, magnified forces can lead to serious problems of wear and instability, as will be seen in the next chapter. Higher forces should not just be compensated for then, we should try to avoid them. And the only way to do this is to avoid sudden changes in velocity.

The ratchet just studied has built-in sudden-changes-in-velocity, of course. The wheel was at rest when struck by a rapidly moving drive arm. Now the wheel must suddenly start to move and the arm suddenly slow down when they collide. This is inherently a questionable design; this type of mechanism should only be used where loads are very light and where low cost is very important. Under these conditions, of course, spring or coil-driven ratchets can give excellent service; witness the highly reliable stepping switch (Fig. P–2 in the Preface, for example). But whenever possible, avoid impact! Or at the very least, impact velocities should be kept as low as possible.

Reducing Forces by Reducing Impact Velocity

One way to reduce impact velocity is to design the ratchet in such a fashion that the driver acquires