Defeating the Devil's Spanner

Keeping aircraft screws and bolts in place is worth considerable effort and expense.

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Machines are marvelous things. They whisk us from place to place in a twinkling. They turn the night into day. They make our clothes and wash them and keep our food from rotting. Less endearingly, they clank and roar and gobble up a large part of the world and what lies under it. They also gradually consume themselves and wear out. More alarming, they occasionally dismantle themselves while in full hum, often to dramatic and sometimes lethal effect.

Some parts of a machine are made separately purely as a manufacturing convenience and then joined in a way intended to be permanent—such as by welding, bonding or riveting. A disconnection here is obviously a structural failure. Other parts are made detachable, either as a concession to the impermanence of moving parts or to permit incidental damage to be repaired without scrapping the whole shebang. Still other parts simply cannot be permanently attached since machines, almost by definition, entail some sort of relative movement of their various parts. In both of these latter cases, connection is usually by threaded fasteners—either screws or nuts and bolts. (Just to get the nomenclature straight, *bolts* are secured by nuts; *screws* are tightened by torquing the head.) These fasteners can fail by rupturing, just like "permanent" joints, but they can also fail by loosening: a mysterious force—the Devil's spanner—works unseen to separate the machine into its constituent parts. When the machine is an aircraft, the consequences do not bear contemplation.

The most rudimentary way to prevent a threaded fastener from loosening is to get enormous leverage and "snug her up real good." Rotation of the bolt or screw head is resisted by friction, the principle being that once the slack is taken up in the joint, further tightening effectively stretches the fastener, causing it to act as a spring that clamps together the two halves. Since the same force acts between the underlying surface and the bolt head (and/or nut) and also between the male and female threads in the assembly, a friction force is generated that resists rotation. More grunt means more resistance to loosening.

Photos: Forbes Aird

Figure 1. Prevailing-torque locknuts use either a soft plastic insert (like the AN 365-A, left) or threads are distorted in some way, such as the AN 363/365-C, right, where the slotted sections are deformed inward. All-metal types have greater heat resistance but tend to be rougher on bolt threads. Locking of the lightweight MS 21042 nut (front) is achieved by triangular deformation of the upper portion of the nut shell.

There are several problems with this approach. First, in some cases the attached bits may be crushed by excessive tightening of fasteners. Ball-jointed rod ends are a good example; wooden or composite structural elements are another. Second, even if damage is not done, the use of a large clamping force just to generate friction may demand a much stronger (and thus heavier) bolt than is necessary to do the primary job of holding things together. Worse, anything that relaxes the tension in the joint reduces the friction, which is the only security against loosening. Relaxation can occur by plastic flow in the bolt or the underlying surfaces, either as a result of overloading the joint or from creep at elevated temperatures. An even more obvious risk is "settling" of any gasket used in the joint.

Still, there are cases where this technique works satisfactorily. If the fastener has to be hefty anyway because it carries substantial tension loads, and it's going to be torqued to near its yield strength to give decent fatigue resistance, a useful amount of locking friction will be produced in any event.

This philosophy is commonly adopted in the assembly of engines (take a look at your cylinder-mounting studs or rod bolts). It works best when the bolt (or stud) is relatively long, since a given amount of "set" in the assembly will have less effect on the preload in the bolt.

A second primitive way to prevent loosening is by *peening*. It's easy: you either wallop the end of the bolt (or stud) with a large hammer until it mushrooms over or—just slightly more subtle—place a center-punch on the face of the nut where the threads emerge and apply a slightly smaller swat. Of course, both techniques also defeat the whole purpose of detachable fasteners and will not endear you to the poor guy who has to undo your handiwork. Doubtless, this is an adequate way to assemble cheap furniture.

It is appropriate at this point to distinguish between two separate problems: first, preventing rotation of a nut relative to a bolt; second, preventing a capscrew or stud from wiggling out of a blind hole. (It is

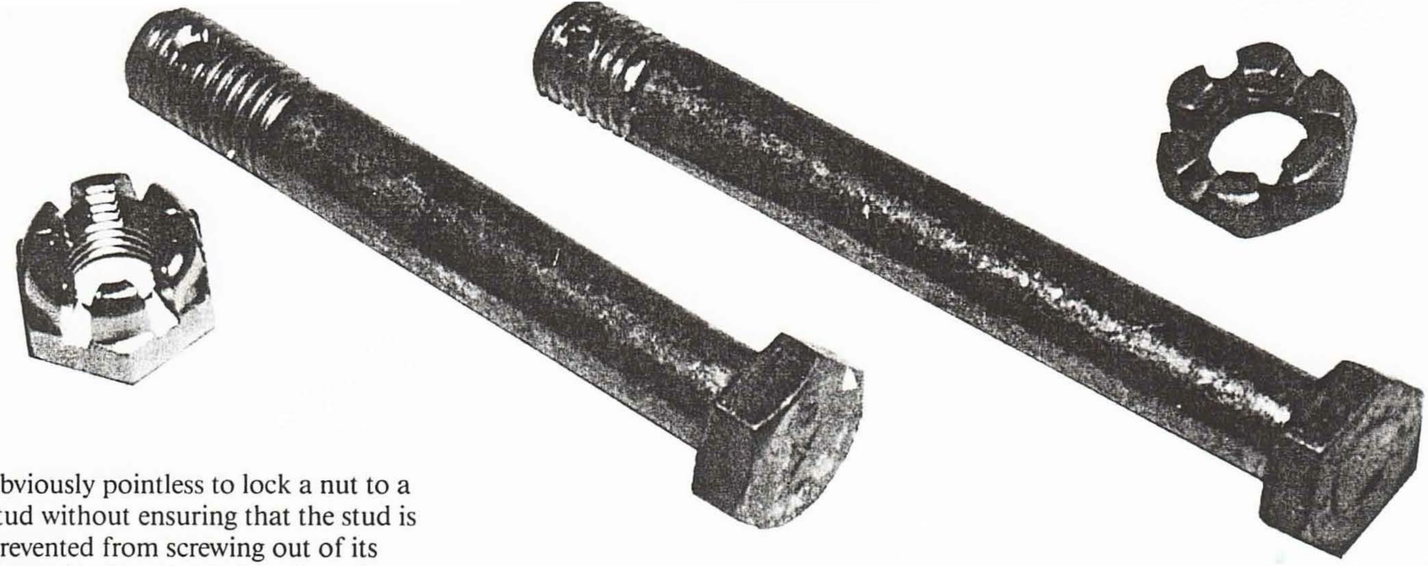

Figure 2. Slotted or castellated nuts are available full height (like the AN 310, left) for tension applications and reduced height (An 320, right) for shear applications only. A cross-drilled bolt for cotter pin insertion is required.

Figure 3. Many Mil Spec bolts and screws come with heads drilled for safety wire, usually specified by adding "H" after the basic part number. Some are available with holes drilled at both head and point.

obviously pointless to lock a nut to a stud without ensuring that the stud is prevented from screwing out of its internally threaded hole; otherwise, the entire exercise amounts to hand-making a conspicuously klutzy and expensive bolt, which is not itself secured in any way.)

Since bolts are—by definition—secured with nuts, an attractive way to secure a nut/bolt assembly against inadvertent loosening is by the use of a self-locking nut, of which there are a zillion different kinds. A few operate on a principle related to the "massive gronk" theory of bolt tightening: everything depends on the axial force existing in the fastener, so these types share the drawback that anything that reduces the normal force also tends to reduce the locking function.

By far to be preferred are *prevailing-torque* locknuts (Figure 1), whose resistance to unscrewing is independent of axial force in the fastener. If the underlying structure is excluded as a grappling point, one of the few things left to hang onto is the male thread. Thus all prevailing-torque locknuts somehow jam themselves on the thread in a way that permits removal without serious damage to either nut or threads, yet provides significant resistance to accidental rotation.

Just how much resistance is required depends on the potential cause of loosening. Recalling that machines have moving parts, the motion at its most complex may entail rapid and repetitive changes in position and velocity. Since the moving parts have mass, they both require and cause force as a condition of their cyclic existence. Regular variations in force and motion are vibrations, which make the spin drier boogie 'round the basement floor and also make your hands and feet too big at certain speeds on certain motorcycles. Vibrations are also a prime cause of machines trying to undo themselves. While self-locking nuts generally show satisfactory resistance to vibration-induced loosening, they deal less well with the simpler case of a slight relative rotation: any place a bolt or screw is used as a fulcrum, something more positive than a prevailing-torque locknut is called for to prevent an unplanned dismantling. The traditional fix employs a slotted or *castellated* nut, secured with a cotter pin (Figure 2). Since these fulcrum applications do not (or at least should not) impose significant tensile loads on the fastener, reduced-height slotted nuts are available for use on bolts with a reduced thread length, both of which save a bit of space and weight.

For those who prefer to wear both belt and suspenders, there is at least one proprietary form of slotted nut that has its castellations deformed inward, so that it operates like a prevailing-torque locknut even if the cotter pin is omitted on assembly or somehow goes missing in service. An even more elaborate version of "belt-and-braces" is the self-retaining bolt, which has a specially profiled split ring fitted loosely into a groove in the bolt shank, just above the threads. The expanded ring requires a significant hammer blow to drive the bolt through the stack of parts to be assembled, then springs open upon reaching fresh air. An even more substantial hammer blow is required to get the bolt back out of the assembly, which discourages the fastener from wandering off the job, even if the nut loses its cotter pin and rattles off.

Be warned, however, that such specialized fasteners are devilishly hard to come by unless you are willing to order at least hundreds of the same size, as they are manufactured to order as a modification of any standard shear bolt. In exceptional circumstances, the search may be worth the effort, though, as the self-retaining bolt provides a reassuring degree of security even if the matching slotted nut (which has a counterbore to clear the split ring) is completely missing, let alone lacking its cotter pin.

Cotter pins can be a real pain: they're tedious to install or remove, there is only one correct size (diameter and length) for each application, they make hamburger out of stray knuckles and forearms and they require a bolt with a suitable cross-drilling in the point (Figure 2). Yet they are undeniably tangible and are usually positive.

Figure 4. A free-running nut with corners drilled for safety wire is one of the few solutions to the need to secure a nut to a stud where the application exceeds the limits of thrust for a prevailing-torque locknut, and the stud itself is locked in place with certainty. This is an MS 9360.

You want tangible? You want positive? How about safety wire? It's cheap, it's light, it is distinctly pretty when well done and it inspires tremendous confidence. It also requires a fancy set of pliers that costs about $50 and it occasionally punches 0.032 holes in your thumb. Like cotter pins, safety wire also demands that the item to be secured have at least one extra hole someplace (Figure 3).

There are certainly places where safety wire is *de rigeur*. For instance, whenever bolts are threaded into a blind hole (in which case they are called capscrews) and there is nothing to grip on the other end, the options are limited: some method can be devised to create resistance within the threads, or a way must be found to prevent rotation of the head of the fastener. In the absence of a factory-made locking-plate of some sort, the easiest and most effective way to prevent the fastener head from turning is with safety wire. Another virtue of safety wire is that it is equally effective on both capscrew heads and on nuts—if you can find nuts with the requisite holes drilled across the corners (Figure 4).

Another means of securing both nuts onto studs and capscrews into holes is the homely lockwasher, beloved of home handymen and shade-tree mechanics everywhere. They are cheap, light, widely available and in some applications they demonstrate remarkable effectiveness. While you're checking out your cylinder-base studs, have a look under the smaller nuts that "stitch" together the perimeter of the crankcase joint. Note, however, that it took engine builders some time (even in the relative security of a dyno-room!) to omit the self-locking nuts previously used in these applications, and it can be reasonably argued that the use of lockwashers in critical applications, just like depending on "massive-gronk" tightening, requires long experience to establish a high degree of confidence.

Apart from grunt-induced friction, none of the techniques so far described deal with the problem of preventing a stud—as opposed to a capscrew—from working its way out of its rightful place. The task here is obviously tougher because, after installation, there is nothing at the visible end to get a grip on (although one occasionally sees studs with a cross-drilling in the end). Thus the task boils down to somehow locking within the threads. For most homebuilders, studs are seldom much of a problem, as there are few places in an airframe where they are called for—studs are mostly to be found in engines. Nevertheless, it's worth taking a look at some of the methods available for

Figure 5. Wire-type thread inserts (left) can be made to lock by distorting a section of the thread form (center). Other inserts, such as the elastomeric device at right, resemble the locking portion of a prevailing-torque locknut.

locking studs in place since, first, most of the available techniques can also be applied to any other threaded fastener and, second, there are circumstances where studs are to be preferred to capscrews; light-metal castings in particular do not take kindly to frequent insertion and removal of screws, so use of a nut, combined with a male threaded fastener that stays put in the casting, has much to recommend it.

Popular among engine builders is the use of an interference-fit thread. Like some other things that engine manufacturers do with threaded fasteners, this technique provides for economical manufacture but should only be depended on to work reliably after protracted development. Less popular with the motor makers is a thread insert with a locking section. (If you stop and think about it, whenever a thread insert is provided, a capscrew could be used in place of a stud and nut because the insert prevents wear and tear on the female threads. The exposed head on the capscrew then provides a grappling point for some other means of locking.)

Locking inserts take various forms (Figure 5). Some seem to be nearly optimal solutions, but other are obviously desperate attempts to fill out a product line after all of the good ideas have been patented. Wire-type inserts achieve locking by distorting the thread form. Sleeve-type inserts provide a locking section that resembles the working bits of a self-locking nut and, like those nuts, may be of all-metal construction or may employ some sort of elastomer. Whatever mechanism might prevent loosening of the stud within the insert, it is clear that equal pains have to be taken to prevent the insert itself from unscrewing. Again, the elegance with which this is achieved depends partly on the inventiveness of the designers but also on the exact size and shape of the loopholes in other people's patents.

Studs (and bolts and capscrews, for that matter) can also be had that include an elastomeric patch or insert of some sort on the threads. Roughly equivalent are male fasteners with purposely deformed threads. Since no additional parts or special tools are required, this arrangement has the virtue of simplicity but, like self-locking nuts, cannot be absolutely depended on in cases where the fastener is used as a hinge or swivel.

There are some other methods of locking studs, which vary from primitive to elegant. In the first category is a version of staking. After installation of the stud, a small drilling is made at the very edge of the hole, cutting through both male and female threads, then a tiny pin is driven into that drilling. In the words of M. Levassor, inventor of the sliding-gear transmission, "C'est brutal, mais ca marche." (It's crude, but it works.) Actually, unless Monsieur Levassor had a free supply of tiny little drill bits (for the installation), of patience and skill (for the removal) and was prepared for the consequences of such a nasty stress-riser, he probably wouldn't have been all that keen on staking of studs. A most inventive and elegant alternative is illustrated in Figure 6.

Figure 6. This Rosan stud ensures positive retention with a separate locking ring. The stud hole is counterbored. After installation of the specially designed stud, the ring is slipped over and driven into the counterbore. Serrations and splines on the steel ring cut into the counterbore and the stud for an elegant, permanent installation.

Since we started off by distinguishing between permanent and detachable connections, we've left for last the whole issue of using thread-locking compounds to glue fasteners together, which blurs the distinction between the two types of joint. Some remarkable claims are made for these "locknuts in a bottle," and doubtless they work very well when used as directed. The biggest problem involved in their use, however, arises from the difficulty of faithfully following those directions: ensuring that the internal threads in a blind hole are completely free of grease, oil or dirt, for example, is easier said than done, especially in the field—obviously you cannot just slobber quarts of the stuff onto any loose-fitting, grubby old bolt and then commit people's lives to the result. Also, since our object is not just to take steps to prevent fasteners from loosening but to be certain that we have succeeded, thread-locking compounds share a problem with other bonded structures—how do we know the bond is sound? Another problem arises if we succeed too well: these tubes of goop come in various grades, from "helps some" to "welds absolutely solid." The strongest grades can lock a stud into a light-metal casting so effectively that the parent metal will fail before the bond. Judicious application of heat may help fastener removal in such cases.

Established airframe and engine manufacturers can sometimes develop their way out of the complexity of cotter pins, safety wire and tricky methods of stud-locking, thereby saving some money for themselves in construction labor and for the owner in subsequent maintenance costs. The flier who "rolls his own" dares not indulge in such economies. In the absence of extended field experience with the type, the homebuilder must strive not for the economically *optimum* method of preventing in-flight dismantling, but for the most certain method—preferably one that gives a positive visual indication of security. The forces of entropy are always at work (remember, rust never sleeps!), disordering the best-laid plans of mice and men; don't let that ol' Devil's spanner put a hex on your hexagons! □