Computer Corner
By Rik Keller

WEIGHT AND BALANCE
Generic Worksheet Number 1

This month we're going to tackle a task that we have all faced with some trepidation—but one that is so vital, so important, so fundamental that it has to be done: the task of calculating our aircraft's weight and balance.

This job is so well suited to a computer's talents that it just begged to be added to this "Computer Corner" column. So, here it is.

The Different Versions

There are about as many different phases that our home-builts go through as there are for babies to grow into their final form. Just as all of these different stages—conception, infants, kids, teenagers and, finally, adults have their disparate needs, so does the birthing of an aircraft have *its* different requirements for a weight-and-balance calculation. That insight led me to construct a few separate and distinct versions of this spreadsheet. That way you can use whichever one best suits your needs. I broke them down into four groups:

1. Your Flying Airplane. This version will be used for aircraft that are already flying. You want to see how your weight and balance change as you burn off fuel during a flight. It can also be used to check that W&B (weight and balance) for different loading conditions: with or without passengers; with or without baggage, with or without a parachute, for examples.
This is the version that we're tackling today.

2. Your Modifications. This one will be useful to those of you that are contemplating adding or removing things from your bird, or re-locating a component. For instance, if the first look at the W&B shows that you are nose heavy, you can see how much it could be helped by moving your battery aft. That will only take you a few seconds to do with this version of the spreadsheet.

3. The Weigh-In. This sheet will help you in finding the final weight—and balance—of your bird after you're through building it. The moment of truth. This is the one to use to do the number crunching after your plane visits the scales for the first time.

4. The Design and Building Phase. This will be the one to use if you're into aircraft design—and for folks that are very early in the construction phase. You can enter the weight and location of each and every component before they're actually installed—or even before they're built,

for all of that. And, if the numbers don't fit what you needed you'll have the time to do something about it.

We'll tackle these subjects one at a time—a different subject every month. This time we start with the easiest task—the one to use for already flying airplanes. It's the one described as number 1 above—"Your Flying Airplane". Next month we'll hit number 2 above and so on.

There's a lot more to this weight and balance business than just doing a few measurements and filling out a form. A reasonable person might ask: "What would happen if I ignored all of this hoopla and just went flying?" I suspect that anyone that's as far into the building and flying business as you are will know the answers to this silly question already. But, just in case someone out there doesn't have a clue as to the utmost importance of this weight and balance stuff, we'll go into it in more detail. But not this month—we have enough to do in simply wrapping our arms around some of the intricacies of the spreadsheets that I've worked up.

They're really pretty easy to use (I hope), so let's get to it.

This Month's Spreadsheet

Today's task is to find the W&B of your own plane—or, maybe, of one that you rent. There are three spreadsheets included here. They're all done with Microsoft's Excel program but, if you use some other program (like Lotus 1-2-3), you should have the ability within that program to convert this to your own use.

The three spreadsheets you'll find included in this article are:

1. One called "Your Plane" that isn't filled out yet so you can use it for your own steed.

2. One named "TF-51 with No Passenger." This is just like the first one except I've filled in data for newsletter editor Ken Simmon's FEW (Fighter Escort Wings) two place version of the stunning F-51 of World War Two fame. One of the most beautiful aircraft ever built, in my humble opinion.

3. The third sheet is entitled "TF-51 with Passenger."

Why did I use the TF-51? For a couple of reasons—first, because it's a tough example. The pilot and passenger are seated in tandem (one behind the other) so there's a noticeable change in the bird's balance depending on whether or not the passenger is on board. It also has a fore-and-aft arrangement for its two fuel tanks. Again, another major weight shift during flight. It turns out to be fairly critical to burn out of the proper tank first. Lastly, Ken was good enough to send me detailed data from the designer, so we had a place to start.

Now, on to the spreadsheet itself.

Let's start with the one entitled "TF-51 with No Passenger."

--Steps one, two, three and four are there strictly for your own records. The rest of the spreadsheet doesn't care if they're filled in or not.

A few notes here. The weight part for each of the items below are pretty straight forward, but the STA (shorthand for longitudinal Station) numbers might not be intuitively obvious. The STA is the pro's term for the distance between a thing called the DATUM and the center-of-gravity (CG) of the item in question. This STA number is normally measured in inches, but there's absolutely no reason why it couldn't be in metric numbers. It'll all work out here either way. This will probably bring up the question: Where do I find the CG of the item? If it's not in your handbook, ask the bird's designer. If *he* won't provide that number, why build someone else's airplane! Or, failing that, eyeball the item and estimate where its center of mass should be. As a for instance, the seated pilot's CG resides in the location of his (her) navel. If the fuel tank has a funny shape, you'll just have to guess. Or fill it with some liquid and find its balance point.

Now, we're only concerned with longitudinal distances here. Fore-and-aft. Nose-to-tail measurements. The left-to-right balance can usually be compensated for by the ailerons.

So, where's that elusive DATUM point? It's somewhere along the length of the airplane; it is almost always chosen by the designer. If not, don't despair—you can choose any place that you want. Like the front of the spinner. Or ten feet in front of that. Or, commonly, the wing's leading edge (LE). If you choose the LE, some things will, obviously, be in front of it and some behind. To handle that problem, use negative numbers for the STA measurements in front of the datum and positive numbers behind it.

The "moment" is found by multiplying the weight by the STA number. It's used to find out how hard each of those items is trying to unbalance the airplane.

--Step 5. You'll need to know the numbers for your *empty* airplane to use this particular spreadsheet. If you don't know those numbers, wait for a future issue of this column. Just enter the STA and weight; the moment will be automatically calculated. If you have the weight and moment only, find the STA by dividing the moment by the weight

--Step 6 is where you enter the numbers for the things that vary from flight to flight. The things that *won't* be weighed when we get to the place where you might put your bird on the scales.

--Step 7. The above steps are the only ones needed to calculate where the plane's CG actually is. Next, we need to know where it needs to be. The plane's kinda like a teeter-totter. We've just found out how much weight is on each end of the board, now we need to find out where the pivot point is so we can keep everything in balance. This step asks you for that info; it should come from the plane's designer. A lot of design parameters go into finding it—some of them are: the type of wing, its shape, and the area and moment arm of the horizontal tail. But, since we're dealing with homebuilt planes here, and this info might not be available, I've added an additional step that you can use to at least get in the ballpark. That's:

--Step 7a. I've tried to make this generic enough to handle several kinds of wing shapes: rectangular (Hershey Bar), tapered and, to some extent, even swept wings. You only need to know (or measure) the STA of the wing's LE (leading edge) and TE (trailing edge) at both the wing's root and its tip. The spreadsheet will then automatically calculate a fairly safe range for the CG (between the 23% and 30% chord distances).

That's it, dude. The spreadsheet will do the rest.

The Inputs for the TF-51

Let's first look at the "TF-51 with Passenger" spreadsheet.

The designer chose the front of the spinner for Ken's TF-51, so that info was put into Step 4.

Step 5. The TF-51 designer also gave Ken the weight and moment numbers for what the designer called a B. E. W.—Basic Empty Airplane (shouldn't B.E.W. equal Basic Empty Weight, Ken?). Those numbers were installed in Cells F25 and G25.

Step 6. These numbers were also from the TF-51 designer. Notice that both fuel tanks are located fore-and-aft as are the pilot and passenger. A VERY tough weight and balance arrangement, but it *does* give the least frontal area so the bird oughta go like spit.

Step 7. The designer, again, furnished these numbers. A much wider C.G. range than is normally found. Usually this range is between 23% and 30% of the wing's chord. This designer's numbers say that you can go clear forward to 14% chord but, as you'll see in a minute, we'll never even get close to it.

That's it for the inputs. Pretty simple, eh? Now, let's see what story these numbers have for us.

Interpreting the Results

Your eye will probably go to the graph first, but the numbers that lead to these lines are given just below that graph.

As you can see, I've separated the weight-and-balances into six separate scenarios. They all have to do with which tank the pilot chooses to burn from first. Series 1 has him burning from the front tank while his aft one remains full. How does the C. G. change as the flight progresses? You can either check the "CG STA" numbers in Column N or look at the Series One numbers in the graph. They show us that:

1. There isn't much of a change in C. G. as the fuel is burned off. We could have predicted this by looking at the numbers for the front tank in the Step 6 data. That tank is located right in the allowable C. G. range but toward the aft end of it.
2. All of the lines are clustered down around the aft C. G. limit.

This same scenario plays out with very little difference through Series 3 when the aft tank is empty.

Series 4 through 6 have the pilot burning from the aft tank after starting with different amounts of fuel in the front tank. Since this aft tank is positioned well behind the aircraft's CG, you'll note a problem arising. When the rear tank is more than half full, the rearward weight shift exceeds the plane's aft CG limit (Series 1). Watch out for this, Ken!

Throwing the passenger out

The aft weight-shift problem is solved when you roll the plane over before the passenger has time to cinch up his seat belt. After he departs the scene, the W&B business settles down pretty much in the middle of its allowed range. Please look at the final spreadsheet called “TF-51 with no passenger.” You’ll now see that almost all of the lines on the graph are safely ensconced within their allowable range. The only one that sticks out here is Series 3—where the aft tank is empty—and Series 1 where its full. But, even here, there’s no danger of exceeding any of the safety limits.

FINAL NOTES

I’d like to point out here how easy it is to find out what will happen when you reconfigure your bird by using this spreadsheet. It took less than 10 seconds to eliminate that troublesome passenger and have the computer redraw the graph.

It’s tough to separate out all of those lines on the chart when they lay on top of each other, isn’t it? Here’s a trick to help you sort them out:

When in Excel, look at the upper right hand corner. You’ll see a number like 75% which tells you what the reduction (or expansion) is in the spreadsheet’s size. If you set it to 100%--or even 200%--those lines will be a lot easier to follow.

WEIGHT AND BALANCE
Adding, Removing or Relocating Hardware
Generic No. 2

As we promised last month when we first tackled the W&B (weight and balance) calculations, this month we'll give you a convenient form to fill in whenever you are considering relocating any hardware in your bird. This will not only tell you what the W&B changes are, but will also show you, graphically and quickly, the effect on your airplane's performance.

It won't tell you whether your machine will go any faster, but will let you know of any possible out-of-envelope balance conditions. And, you say, why would I want to know this? Because if the balance isn't right you could crash and burn. How? Read on.

CG too far aft

This is the worst case. It can, and has, led to instability and loss of control. Particularly in a stall—you might not be able to lower the nose for recovery.

An interesting side light here—the farther aft that you get the cg (center of gravity) the more efficient your plane will be. That's because, as you may know, the wing may be lifting, but the tail is pushing downwards. This appears to the wing to be a more heavily loaded bird. That seemingly heavier machine will go slower and burn more fuel. So why did the designers create this strange condition? As a matter of fact, those designers went to quite a bit of trouble to make certain that the horizontal tail *would* push down instead of carrying its rightful share of the weight.

All designers don't make this mistake; just check out most of Burt Rutan's birds. Those funny looking ones that have their horizontal tails in *front* of the main wing. The canards (or, in French, the ducks—because of what they look like when they're flying overhead) where the front-mounted tail manfully does its share of lifting. What does Burt know that has escaped all of the others? And, do you have to give up anything in order to get that tail to lift? It kinda makes a guy wonder—particularly when Burt seems to have moved the tail back to the rear on all of his latest machines. It turns out that you *do* give up quite a bit—including *much* longer takeoff runs. But let's get back to why you need to very carefully balance your bird.

The Basics of Balance

The whole idea here is to have your plane attempt to keep some "trim speed" constant. If it can do that all by itself, it will fly nearly hands off. Let's see how that can be managed.

Consider this scenario: you take off, climb to altitude, then level out. After the bird gets up to whatever speed you've picked, you pull the throttle back and then roll the trim in until you can let go of the stick (or, for you spam canners, the wheel). The plane will then pretty much keep that same airspeed no matter what gusts or burbles you encounter. It also seems to want to stay at that same speed even as you burn off fuel, as the plane gets lighter, as the weight and balance changes.

How does it do that???

Let's look into what's happening minute-by-minute so we can track down what it takes in the weight-and-balance business to achieve this behavior. This thing called "dynamic longitudinal stability".

Because of those anomalies in the atmosphere, the plane constantly speeds up or slows down just a bit. Whenever the speed tends to slow, if you can get the nose to drop, it can go downhill to regain that speed. If the bird speeds up you'll want the nose to rise so you will scrub off that speed—will trade it for a few feet of altitude.

Now let's see what happens if the tail is helping to lift the plane. When the bird slows down, clearly the tail will lift less. This would tend to let the tail drop—which is the same as having the nose rise. When the nose comes up, the bird will climb—which will make it slow down even more. This could, conceivably, continue until the nose was pointing straight up and your speed was zero. Probably not where you'd want to be.

Since this plan didn't work, let's see what happens if the tail is made to push downwards—to create negative lift. Now, when the speed decays, the tail will quit pushing downward so hard—which will let it rise. This causes the nose to drop. This will let the speed build back up to where it was when this mess started. Dynamically stable, it's called. You can go through the same exercise in reverse and see that an increase in speed will make the nose go up a bit to bleed that speed right off.

Now that we can see the need for the tail to be pushing downwards, improbable as that seems, how can we get it to do that? By having the weight on the teeter-totter forward of the pivot point, that's how. Or, in more elegant terms, by having the cg (center of gravity, the plane's balance point) in front of the c.p. (center of pressure), its pivot point.

How do we tell where these two mythical points are? That's the whole purpose of this weight and balance exercise. The combination of weights and moment arms[1] will tell you where the cg is. True, it will change as you add passengers or burn fuel, but you can put limits on those and find out

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[1] To learn about moment arms, please look at last month's column.

where the front-most and rear-most points will be. This spreadsheet will tell you that. Now what about the c.p.—the fictional point on the wing that describes where the lift is coming from. That will always be about one-fourth of the way back from the front of the wing to the rear of the wing—called the quarter chord point. That, too, changes with speed—it tends to wander rearward as you go faster. The aerodynamicists call this c-sub-m, the moment coefficient.

So how does the designer account for these real life changes? By building a horizontal tail powerful enough to counteract those changes so the whole rig will stay in balance. If it isn't mighty enough, he will either have to make it larger or place it further to the rear—give it a longer moment arm, a longer tail boom. Since both of these moves add structure, they will also add drag and weight. So he will, as usual, find some compromise, and tell you in no uncertain terms where you can safely put your cg. He'll do that by telling you the "forward and aft cg limits"—the numbers that we'll then put in Cells D44 and E44 of the spreadsheet.

CG TOO FAR FORWARD

You can probably guess what would happen if you added a much heavier weight to the front of your bird. The very best thing that could happen would be the inability to get your nose up for take-off. This, at least, would eliminate the next worse problem—the fact that it might be next to impossible to get that nose up for the next landing. This is made worse by the fact that you'll be in ground effect then which makes it even harder to raise the nose. These problem are bad enough, but just to add insult to injury, having all that weight up front will make the tail feathers have to push down harder just to keep everything in balance. Which gives the wing more weight to lift—which takes more engine power—which burns your gas off faster—ad nauseum. Not good.

THE SPREADSHEET

Now that some of the reasons for keeping the bird's balance within the range proscribed by the designer, let's get to the spreadsheet—which will help us to do just that.

As you will remember from last month, we used a spreadsheet very similar to the one that you'll see today which gave you the W&B (weight and balance) figures for your existing, flying, airplane. The sheet this month will give you a quick take on how that W&B will change whenever you:

-Move
-Remove or
-Add

a piece of hardware. Like a radio. Or a new fuel tank. Or a battery. Or a whatever that you're thinking of relocating on your plane.

Instead of repeating all of the instructions that were given last month, may I suggest that you tune your Internet browser to:

htp://www.eaa14.org

and download the whole shebang. You can also download this month's spreadsheet at the same time if you'd like. Saves a whole *lot* of work.

The only changes were the addition of Step 6. Step 6.1 gives you a place to *add* something, Step 6.2 a place to *remove* something and Step 6.3 tells you what to do if you just plan to re-locate that something.

There are three spreadsheets here; the first one is for you to use for your plane. The second one has the numbers added to it from Ken Simmons' FEW TF-51, the example that included the passenger. As we saw last month, this led to an out-of-envelope balance problem. It was tail heavy when both fuel tanks were full—what we labeled as Series 1. As we noted above, this could get Ken into an unrecoverable stall. Might not be too bad for *him* since our example had Ken wearing a parachute. But his parachuteless passenger *might* object to this indignity and it would be a shame to lose such a beautiful aircraft.

So, what to do? Many choices; as an easy way out I chose to add weight to the frontmost part of the bird—the spinner. Adding a mere 20 pounds here completely solved the problem—as shown in the third spreadsheet. That twenty pounds added a mere 1% to the total weight.

Note:

You probably knew that you must use FAA Form 337 whenever you move, add or remove a major piece of equipment. That form requires you to enter the W&B changes to the "appropriate aircraft record". You can use the numbers generated by this spreadsheet for that.

NEXT TIME

Next month we'll give you a spreadsheet to use for your initial weigh-in. The moment of truth. When you will discover for the first time just how bad your W&B problem really is.