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Hidden Errors in Turbine Blade Moment Measurement and How to Avoid Them

by

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1 Abstract By first measuring the static moment of the individual blades and then sorting them into the ideal order, jet engine manufacturers have found that they can greatly reduce the time and effort required to balance the rotor of an engine. More recently a new concept has emerged: if a computer record is kept of the moment of every blade in every engine manufactured, then a damaged blade can be replaced with one of identical moment without the need to disassemble the engine and rebalance the rotor. This saves both money and time, but it places new demands on the accuracy of the moment measurement. If blade moments are in error, then the engine will be unbalanced, resulting in premature wear, or possibly a fatal accident. The concept of blade replacement by matching blade moment requires that the blade be measured with a high degree of accuracy. For example, a 35 pound fan blade might have nominal moment of 17,000 oz-inch and need to be balanced to within 0.5 oz-inch. This represents a required measurement accuracy of 0.003% of value!

Space Electronics manufactures instruments to measure turbine blade moment (these instruments are often called "moment weight scales"). Our instruments use a new technology which is as much as 40 times more accurate than the conventional knife-edge and load-cell technology that has been employed for the last 30 years. As a result, the moment measurement error of our instruments can be considered insignificant. This has led us to more clearly identify other sources of measurement error which appear to be widespread throughout the industry. The problems show up in two ways: (1) a blade is replaced in the field with one of supposedly identical moment, and the engine is then found to be unbalanced; (2) a set of blades is measured at Plant A and then sent to Plant B for installation in the engine. If the blades are measured at Plant B before they are installed, the data differs from the original set of measurements. However, it often isn't just a simple change in scale factor (i.e the blades aren't just 0.5% higher in moment at Plant B). There are several factors involved, resulting in what appears to be random differences. I believe I have identified the sources of these errors. This paper identifies each type of error, and gives recommendations for their elimination.

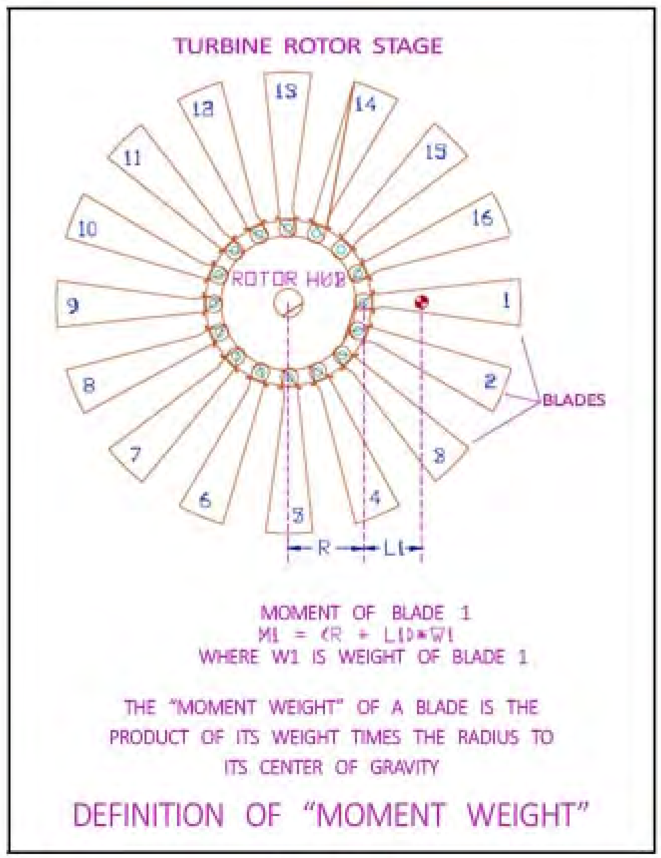


Figure 1

2 Introduction The moment (or "moment weight") of a turbine blade is simply the product of its weight times the distance from a reference axis to its CG. There are three moment weights for any turbine blade: radial, axial, and transverse (see figure 1). The axial and transverse moment weight are always measured relative to the central ("stacking" or "datum") axis of the blade. Radial moment weight is usually defined relative to the center of rotation of the turbine rotor, but sometimes is defined relative to the Z-plane at the root of the blade.

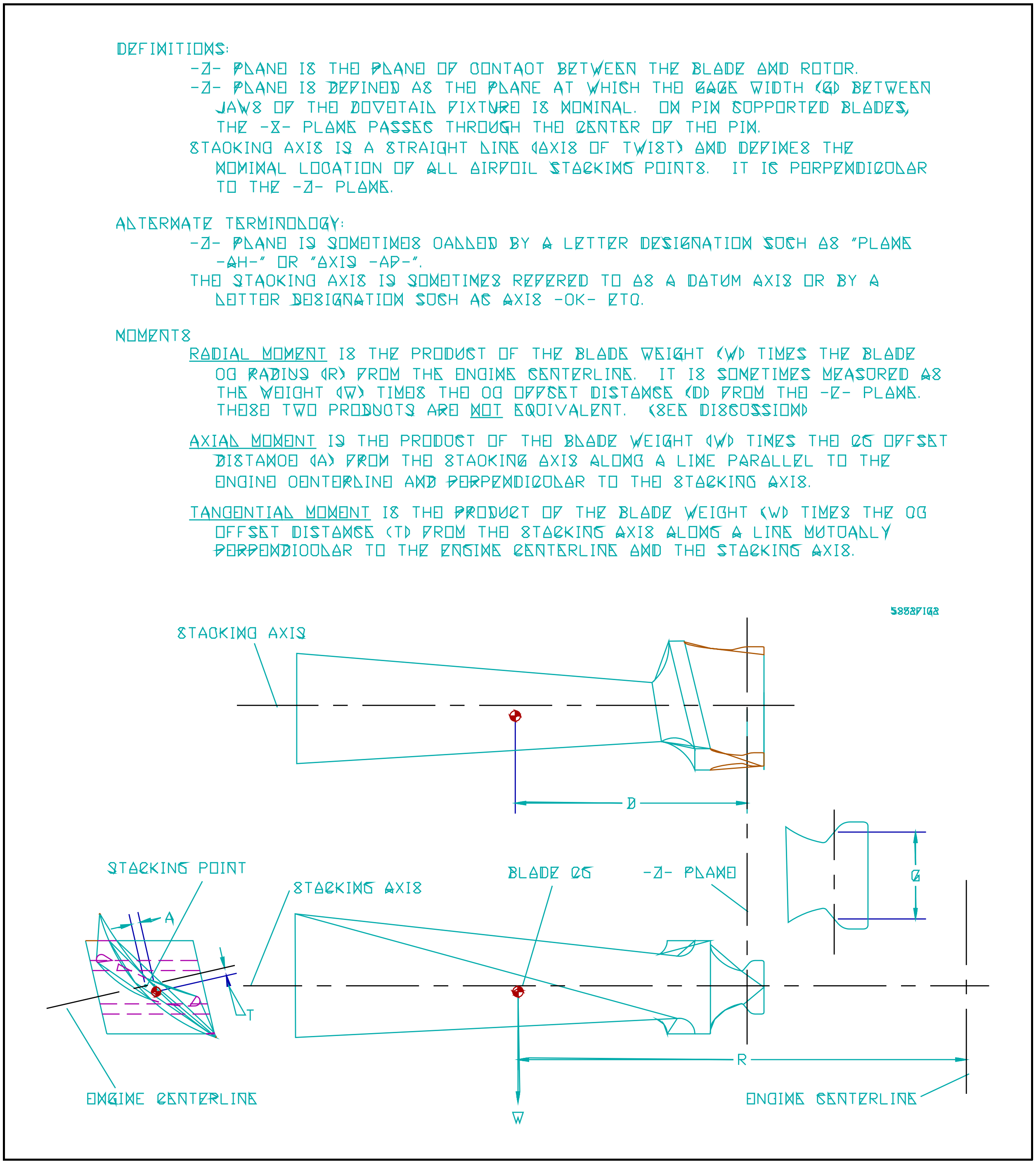


Figure 2

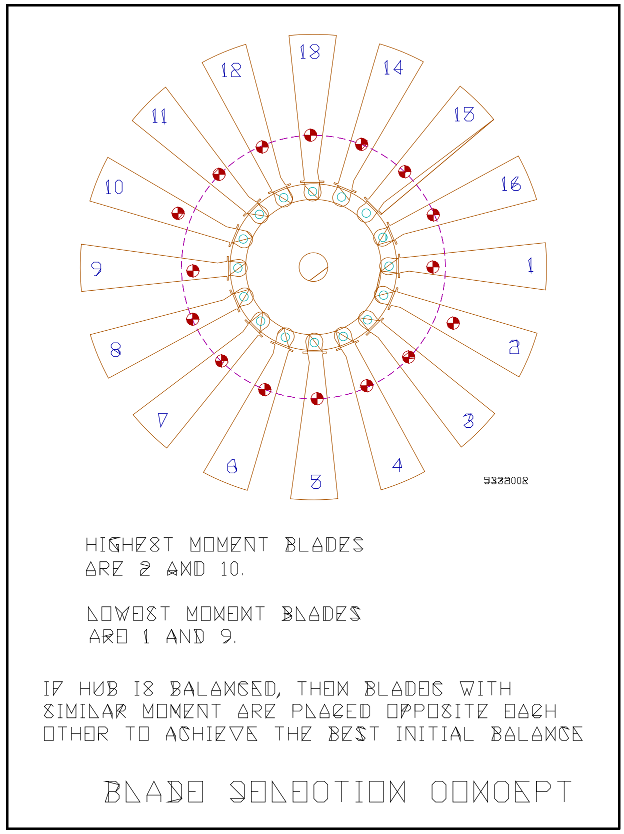


Figure 3

For a turbine rotor to be perfectly balanced, each disk or "stage" on the rotor must be individually balanced. This in turn requires that the stage be assembled with matched pairs of blades which are oriented at 180° from each other. See SAWE Paper #2244 "A New Moment Balance Machine for Turbine Blade Measurements" by Richard Boynton and Kurt Wiener for a more complete description of the steps required in balancing a turbine rotor. The blade pairs must have identical radial moment to prevent a CG offset in the stage, but also the axial and transverse moments must be matched to prevent product of inertia unbalance (i.e. "dynamic unbalance"). If it is not possible to find matched pairs, then a computer program such as the Space Electronics "BLADEBAL" software can be used to obtain the best fit solution to the balance problem. In addition to selecting blades for optimum balance, this program also arranges the distribution so that there is a minimum distortion of the rotor hub due to centrifugal force.

A turbine rotor is made up of a number of stages. Generally there is a large difference in the size of the blades in the various stages. Since they all are mounted on the same shaft, the unbalance tolerance is the same for all stages. If the rotor is made up of 35 pound fan blades at the forward end and 1 pound blades at the aft end, then the unbalance of the fan blades is 35 times more critical than the smaller blades. Generally, this means that 3-axis moment measurements are made on the heavier fan blades, and a very sophisticated computer program selects their location; only radial moment is measured on the lighter blades. In some cases, the lighter blades are only matched by weight and no effort is made to measure their moment.

2.1 Back to the original question: why can't I get repeatable moment weight data? At Space Electronics, we are frequently asked this question. The answer is:

1. The accuracy of your moment weight machine is not as good as you think it is.

2. The blade adaptor does not consistently hold the blade in exactly the same position.

2.2 Moment weight machine error Although moment measurement problems are often traced to the adaptor, you should always evaluate the moment weight scale first before undertaking the more difficult task of evaluating the adaptor.

We frequently hear a similar story: a certain moment weight machine always gets the same answer when measuring the master blade, but it shows considerable variation if a particular production blade is measured one day, and then this same blade is measured on another day. How is this possible? While there are several explanations for this, at Space Electronics we have found that the most common situation is that the machine does not get consistent data for the master blade. The reason this is not apparent is that the operator knows what the moment should be for the master blade. He has been told not to begin measurements if the moment weight scale doesn't measure the master blade moment within a certain tolerance. Therefore, he keeps measuring it until he gets the right answer. If necessary, he adjusts the rest stop on the adaptor, or presses the blade one way or the other until the answer comes out within the tolerance required. Basically, the operator is just kidding himself. If it takes 10 tries to get the right answer for the master blade, then the chances are 1 in 10 that he will get a valid moment measurement on a production blade. However, since he doesn't know what the answer should be for the production blade, the operator accepts the first answer he gets.

I'm not suggesting that the operator intentionally falsifies his data. The mind can play tricks on you without you knowing it. This phenomenon is the reason medical researchers use double blind studies when evaluating the effect of a new drug. In some instances, the written procedure for moment weight measurement may instruct the operator to make adjustments until the measurement is within the specified tolerance.

3 Advanced moment weight scale technology Most manufacturers of turbine blade moment weighing scales use the same technology: a knife-edge pivot and a strain gage load cell. Machines manufactured by Space Electronics use crossed-web flexure pivots and force restoration technology, resulting in a measurement instrument which is 10 to 40 times more accurate than other methods and is also more rugged and resistant to damage in a production environment.

3.1 Problems with knife-edge pivots Most moment weight machines on the market use a knife edge to form the pivot axis. This technology was developed in the 1800's for the pivot in beam balance scales used in precision weighing. There are a number of problems associated with this type of pivot. The problems listed below will explain why Space Electronics does not use this type of pivot.

3.1.1 Problem: knife-edge pivot wear and damage In order to create a precise pivot axis, the knife edge must be very sharp. For example, consider a machine whose accuracy is 0.1 oz-inch when measuring a 40 pound blade. If 1/3 of the error budget is allotted to the pivot error, then the knife edge must be less than 0.000,050 inch wide! After the machine is used for many measurements, this edge becomes rounded, with the result that the point of contact moves forward toward the turbine blade as the load cell in the machine is deflected. This causes the radius of the turbine blade to decrease, resulting in a measurement error.

3.1.2 Problem: a 0.000,050 inch wide knife-edge is very fragile If the operator of the machine shock loads the machine during loading or unloading of the blade, the delicate knife edge can be damaged. This will cause an instantaneous change in moment accuracy. There is no way the operator will be aware of this error unless he calibrates his machine on a daily basis.

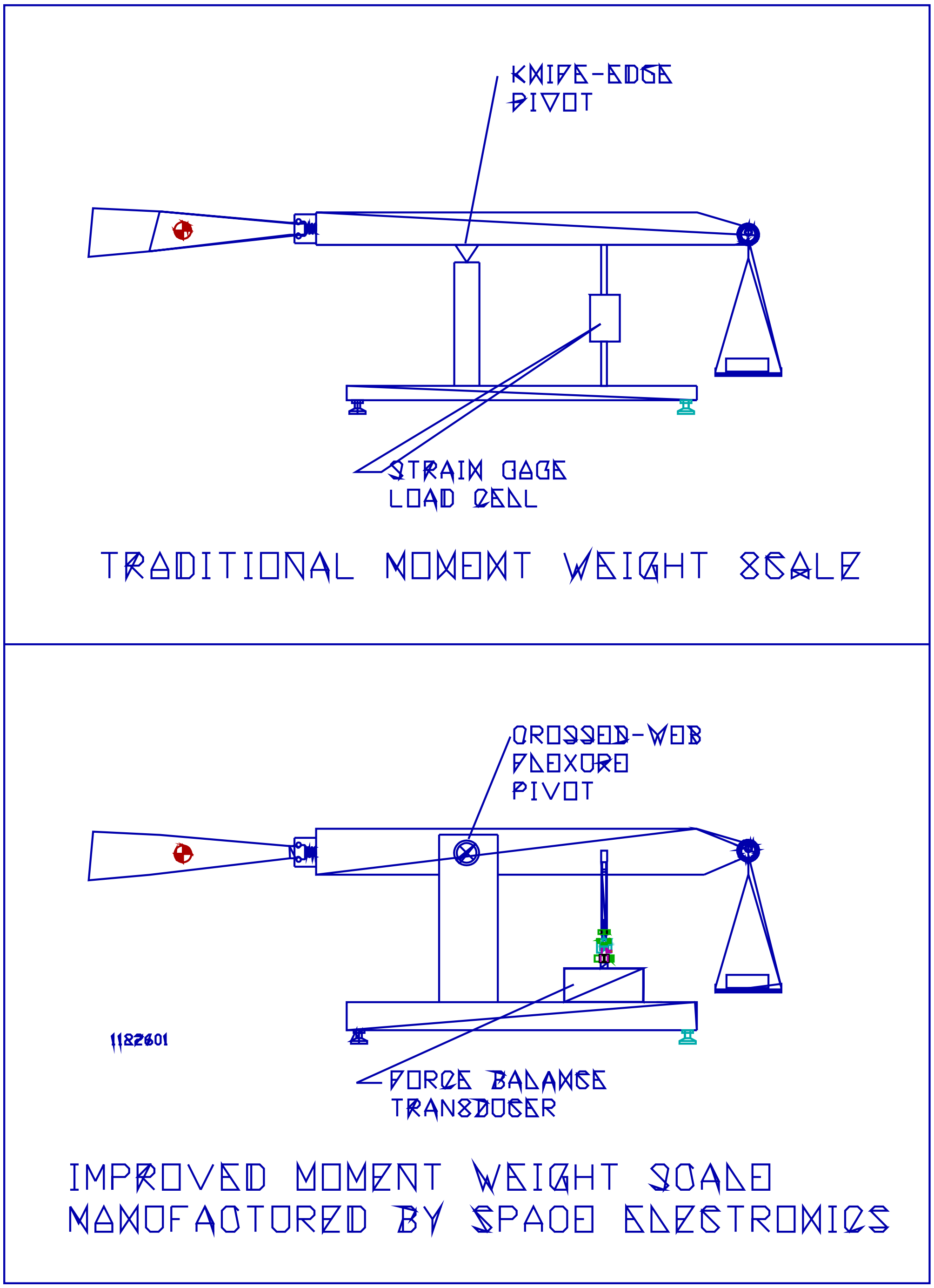


Figure 4

3.1.3 Problem: hysteresis in the knife edge pivot Since the knife edge bears against a flat or slightly curved plate, damage to the knife edge can produce a condition where the pivot is stable in two different positions. This results in an unexplained shift in moment reading; if you press down on the blade and release it, you get a different moment reading than if you raise the blade and release it.

3.2 Crossed-web flexures form an ideal pivot axis Twenty five years ago Space Electronics discontinued the use of knife edges and substituted crossed-web flexures for the pivot axis. This is the same technology used by the National Institute of Standards and Technology in their most accurate beam balance scales. Crossed web flexures create a perfect pivot by employing strips of spring steel oriented at right angles. There is only one point where the combination of these strips can bend. Since there is no relative motion, there is no friction. There is no surface to wear. The location of the pivot axis is fixed relative to the machine. This type of pivot eliminates all of the error sources described above.

Flexures introduce a small but not insignificant torsion spring into the system. If you use a load cell to measure force, then this introduces a non-linearity. One solution would be to use a very delicate crossed-web flexure for a pivot. However, this thin web would be easily broken, making the scale unreliable. Space Electronics machines use a thick web flexure which is very rugged. We also use a force restoration transducer which has almost unmeasurable deflection, so that the spring rate of the flexures is eliminated. It would not be possible for us to use a rugged flexure if we had any significant deflection in our force transducer.

3.3 Problems with strain gage load cells Space Electronics moment weight machines do <u>not</u> use strain gage load cells. We have found that these load cells do not have the accuracy and durability required for the measurement of turbine blade moment.

3.3.1 Problem: strain gage load cell deflection A strain gage load cell is basically a passive spring. The deflection of the spring is a measure of force. Full scale deflection depends on the type of cell and can be as much as 0.040 inch. Because of this deflection, the geometry of the moment weight machine is different when measuring different moments. Any mechanical non-linearities will reduce accuracy.

3.3.2 Problem: CG height limitation When measuring wide fan blades a subtle error is introduced: since the CG of the blade is not necessarily at the same height as the measurement axis of the machine, the load cell deflection causes the CG to lean outward or inward, altering the measured moment. <u>The Space Electronics machine uses a transducer which does not deflect significantly, so this problem does not occur with our machines.</u>

3.3.3 Problem: load cells are easily overloaded and damaged In order to achieve significant strain, a strain gage load cell must be stressed to a high percentage of its yield point. Usually a load cell will be permanently damaged if the force applied exceeds 150% of full scale. Many moment weight machines use a lockout mechanism to protect the cell during loading of the blade. If the operator forgets to use this mechanism, then the cell can be damaged. We have found that these lockout mechanisms are often a cause of non-repeatability. In contrast, the Space Electronics machines do not use a strain gage load cell and are so rugged that they require no lockout mechanism.

3.3.4 Problem: drift Although the load cell output can be amplified to obtain a resolution of 0.002%, this resolution is useless, since the thermal drift in the load cell is generally 10 times greater than this. In other words, the moment output might be able to read an increment as small as 0.1 oz-inch, but the drift could be as great as 0.5 oz-inch in 10 minutes.

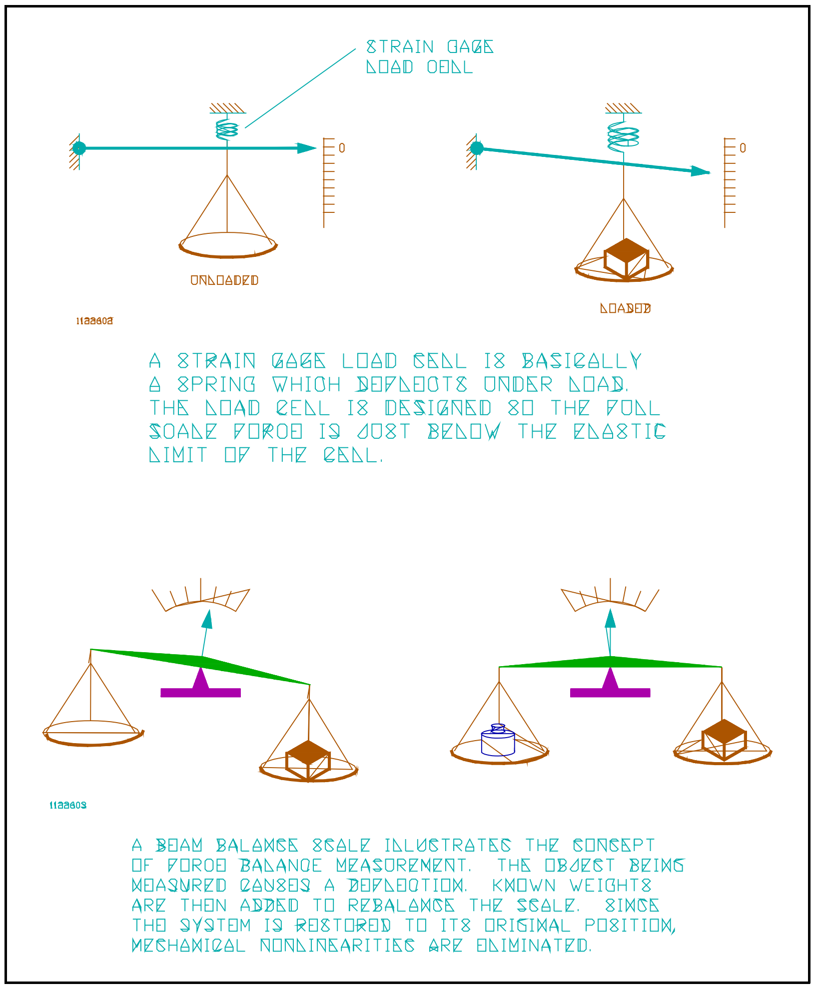


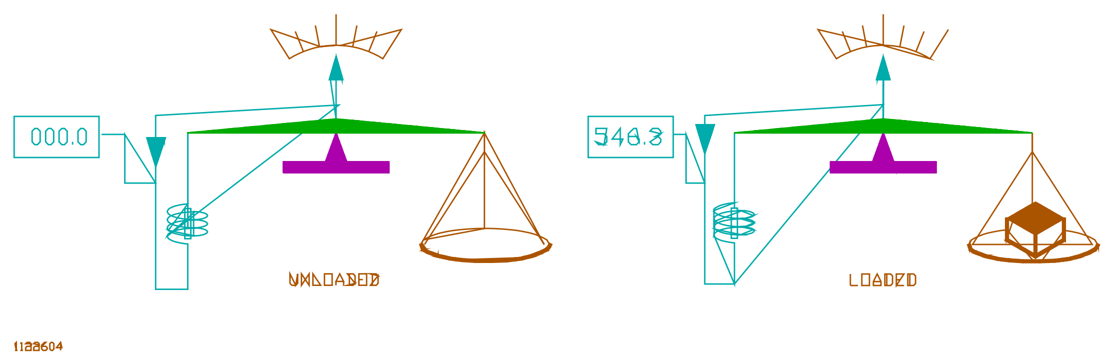
Figure 5

3.3.5 Problem: bending moment error A typical strain gage load cell has a specified accuracy of about 0.05%. However, this specification does not include the effect of bending moment on the cell: if the cell is not loaded directly on its axis, it will exhibit an error due to the bending of the beam within the cell. In some instances, this error can be in the order of 1% or more.

3.3.6 Problem: signal to noise ratio A typical strain gage load cell has a full scale output of 0.03 volts. Therefore, to achieve an accuracy of 0.05%, the induced electromagnetic noise must be less than 15 millionths of a volt! Therefore, full accuracy is only possible in an environment which is free of electrical noise. This is rarely the situation in a gas turbine assembly plant.

3.4 Force restoration technology Rather than using strain gages to measure the unbalance torque on the beam, we apply an equal and opposite electromagnetic torque to return the beam to its original level condition. This technique results in linearity of better than 0.01% and dynamic range of at least 100,000 to 1. Since this is a closed-loop transducer, there is effectively no deflection. The transducer is not sensitive to bending moment. The output voltage is approximately 20 volts (1000 times larger than a strain gage load cell). Therefore, electromagnetic noise has negligible effect on accuracy.

3.5 Electronic Dashpot In the early days of blade balance, the old load cell type moment weighing scales used an oil dashpot to damp the vibration of the beam. The oil dashpot had the disadvantages that the oil would often leak out during shipment, and it was subject to contamination. It had to be adjusted carefully to prevent rubbing. The Space Electronics machine incorporates electronic damping in the force restoration transducer. This accomplishes the same task as the oil dashpot, but has none of the disadvantages.



THIS ILLUSTRATES THE CONCEPT OF A FORCE BALANCE TRANSDUCER. A LASER SENSES THE DEFLECTION DUE TO THE LOAD, AND INCREASES THE CURRENT TO THE COIL UNTIL BALANCE IS RESTORED. THE WEIGHT OF THE LOAD IS PROPORTIONAL TO THE CURRENT. THIS METHOD HAS SEVERAL ADVANTAGES:

1. THERE IS NO MECHANICAL NONLINEARITY, SINCE THE TRANSDUCER ALWAYS RETURNS TO ITS NULL POSITION.

2. THE OUTPUT VOLTAGE IS ABOUT 20 VOLTS. A STRAIN GAUGE LOAD CELL TYPICALLY HAS AN OUTPUT OF 20 MILLIVOLTS. THEREFORE, THE FORCE BALANCE TRANSDUCER HAS A SIGNAL-TO-NOISE RATIO WHICH IS 1000 TIMES BETTER THAN A LOAD CELL.

Figure 6

3.6 Testing for repeatability Although repeatability is not the same as accuracy, a moment weight measurement is certainly no better than its repeatability. The simple tests described in the following sections can be used to detect and identify causes of non-repeatability.

Test 1. Place the master blade in the machine and measure its moment. Then leave the blade in the machine for 20 minute without disturbing it or the machine. Measure and record the moment once every minute. All the measured values should be the same. Any variation is caused by machine error or environmental disturbances. For example, if the measured moment varies by 1.2 oz-inch over a 20 minute period, then you know that the accuracy of your machine is no better than 1.2 oz-inch (and is probably worse than that). If the machine passes test #1, then skip to test #6.

3.7 Eliminating environmental factors A variation in moment reading can be due to drift in the moment weight scale or it can be due to environmental factors such as ground vibration and drafts. The following tests identify any environmental problems.

Test 2. If the measured moment varies in test #1, then measure the ambient temperature to see if there is a change of more than 3° F over the 20 minute period. This could be the cause of data variation.

Test 3. If you determine that temperature change is not the problem, then surround the machine with a shroud to exclude drafts, and run test #1 again.

Test 4. If covering the machine didn't solve the problem, then run test #1 at night or early in the morning when there is no lift truck traffic or other causes of ground vibration.

Test 5. If the problem is not temperature variation or drafts or vibration, then you have a defective machine.

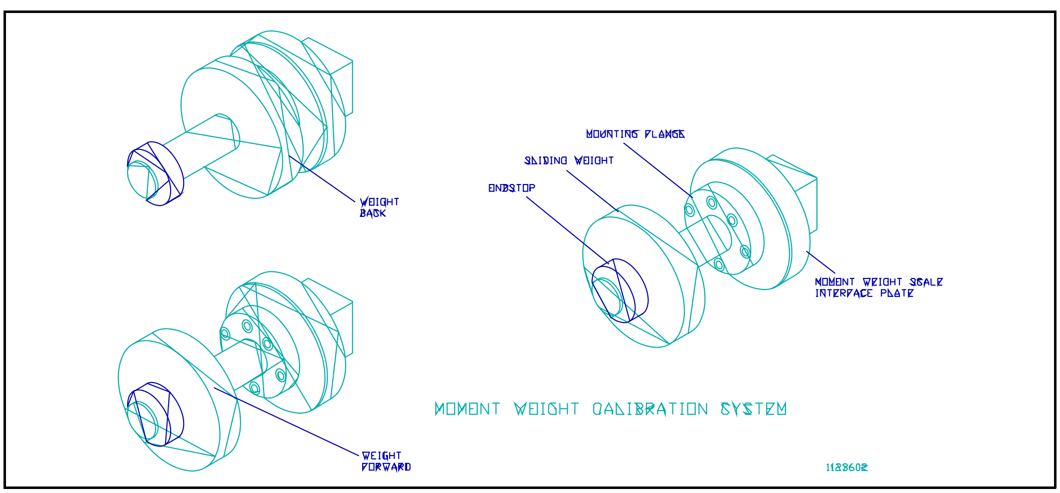


Figure 7

3.8 Accuracy verification

Test 6. If the random variation in readings is within acceptable limits (as determined in test # 1), then the next test is to determine the accuracy of the machine. It is relatively easy to determine the mounting plate radius of a moment weight machine. This requires a calibration rod and a weight of precisely cylindrical shape (i.e. better than 0.0001 inch) as shown in Figure 7. The mass of the weight is determined by weighing it on a very accurate scale. Since the shape is a perfect cylinder, the CG distance is 1/2 the thickness. The calibration rod mounting flange is machined so it is flat and parallel and its thickness is measured within 0.0001 inch. This calibration system attaches to the mounting plate of the moment weight scale.

The readout of the moment weight scale is set to zero with the mounting flange and rod in place (the end stop is not used for this procedure). Then the weight is added, taking care to press it tightly against the mounting flange, so that the distance between the weight and the mounting plate of the machine is exactly known. The resulting change in moment is then measured. The distance between the pivot center of the machine and the face of the interface plate is then calculated:

where R = radius of interface plate

M = measured moment due to addition of weight

W = weight of calibration mass

A = Thickness of calibration rod mounting flange

T = thickness of calibration mass

Test 7. **Moment linearity** can be determined by measuring the moment change using a set of precision weights of differing mass. The procedure for measuring the moment change due to a weight is: Slide the weight onto the rod. Screw the endstop in position onto the end of the rod. Press the weight to one end of the rod. Zero the moment scale. Then slide the weight to the other end of the rod and measure the moment change. The true moment change is:

$$M_1 = (W_1)(L-T_1)$$

where

M_1 = moment change due to movement of calibration mass #1 from one end of rod to the other

W_1 = weight of calibration mass #1

L = length of rod from face of mounting flange to face of endstop

T_1 = thickness of calibration mass #1

4 Adaptor errors If you have determined that your moment weight machine is accurate and repeatable, then your problem must be due to fixturing (tooling) error. The accuracy of a turbine blade moment weight measurement is directly related to the accuracy of the adaptor (fixture) used to mount the turbine blade at a precise radius relative to the moment weight machine. Blade adaptor error is generally the major source of error when using any type of moment weight machine. Since blades of different sizes are assembled onto the same shaft, the balance tolerance is the same for all size blades. Larger blades do not have a less critical moment tolerance. Therefore, adaptor accuracy is most important when measuring heavy blades. For example, if you want to measure a 35 pound blade with an accuracy of 0.5 oz-inch, and you budget 1/3 of this error for adaptor error, then you need an adaptor with radial accuracy of 0.000,300 inch.

4.1 Adaptor radial moment reference The purpose of measuring turbine blade moment weight is to sort pairs of blades for equal moment relative to the center of rotation of the engine. This will result in a balanced condition (provided the rotor hub has the same Z-plane radius for each pair of blades). There are two ways of accomplishing this objective:

4.1.1 The blade can be fixtured in the moment weight scale such that its Z-plane is at the same distance from the pivot center of the scale as its Z-plane is from the center of rotation of the engine. The measured moment will then relate directly to the unbalance moment in the engine, and no correction is required.

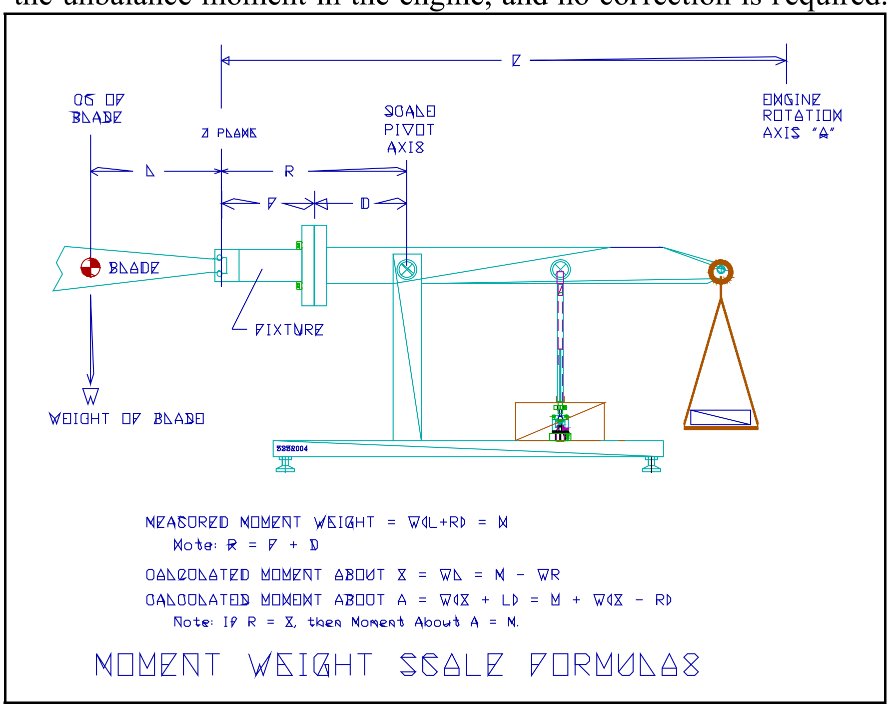


Figure 8

4.1.2 The blade can be fixtured in the moment weight scale such that its Z-plane is NOT at the same distance from the pivot center of the scale as its Z-plane is from the center of rotation of the engine. A mathematical correction will then be required to convert the measured moment to a moment relative to the engine Z-plane radius. This correction requires that you measure the weight of each blade. Space Electronics manufactures scales which measure both weight and moment and make this correction automatically.

There is a common misconception that a rotor will be balanced if it is assembled with matched pairs of blades having the same moment relative to the Z axis. This is only true if the blades have identical weight--an unlike coincidence. Consider a moment weight scale with an adaptor whose Z-plane radius is 6 inches. The Z-plane radius for the blade in the engine is 14 inches. Assume that a blade which weighs 400g and a blade which weighs 380g both have the same measured moment. If no correction were made, then it would seem that these two blades could be used as a matched pair in the engine. However, when the moment weights for the two blades are converted to the correct engine radius, their values differ by 160 g-inch!

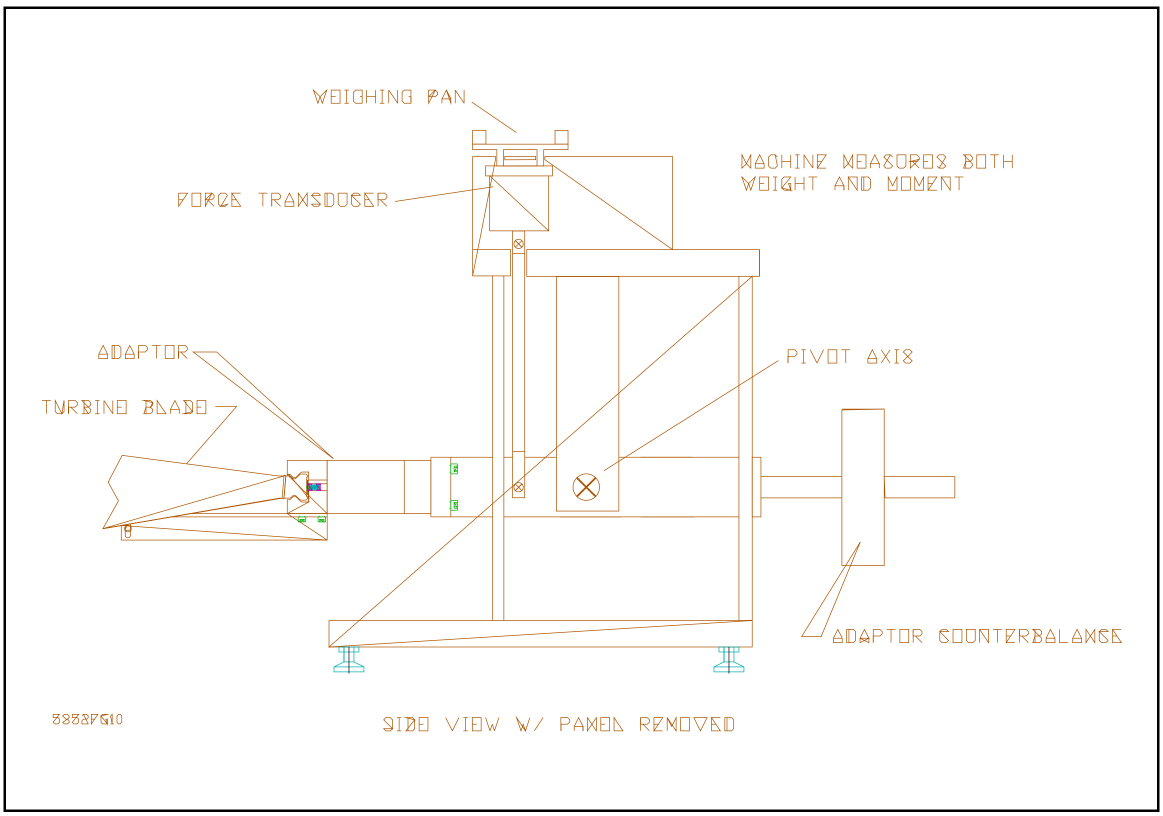


Figure 9 Concept of Space Electronics SE9987 series Moment Weight Scale

We have found that a number of turbine rebuilding facilities are not aware that a correction is required if the adaptor does not hold the blade Z-plane at the correct radius. This can lead to serious unbalance problems if damaged blades are replaced in the field by matching the moment weight of the original blade with the replacement blade. It is not possible to make the correction unless you know the weight of each blade.

CAUTIONARY NOTE: Even if a blade is replaced with one with a moment weight which is identical to the recorded moment weight of the original blade, there may still be some unbalance, since the blades wear and their moments probably have changed. A more accurate balance can be obtained by removing all blades, remeasuring them, and them using a computer program such as the Space Electronics BLADEBAL to select the best arrangement in the rotor.

It might appear logical to always design the blade adaptor such that the Z-plane is at the nominal engine radius. However, this is not always possible, and sometimes there are practical reasons for not doing this. Most blade moment weight scales have a mounting surface radius of 5 inches or more, and the adaptor usually adds at least 1 inch to this radius. If the Z-plane is less than about 6 inches from the center of rotation of the engine, then it will be necessary to measure the moment at a larger radius and perform the mathematical correction. Another case where correction is required is the situation where there are a number of blades of identical root configuration but differing Z-plane radius. Rather than constructing a number of different adaptors, the most practical solution is to use one adaptor and correct the measured moment. This saves the cost of the additional adaptors, and eliminates the need for the operator to keep changing adaptors when measuring a variety of blades.

Space Electronics manufactures a series of scales which measure both weight and moment and make the required radius correction automatically. The operator simply keys in the blade type before measuring a series of blades. The Space Electronics computer then chooses the correct formula to convert the data and print the moments relative to the correct Z-plane radius.

4.2 Adaptor radial accuracy If you are measuring a single set of blades and are only concerned about the <u>relative</u> moment between blades, then the exact radius of the adaptor is not as critical. However, if you are combining blade with those measured at other facilities, or you are using the moment values to replace blades that are damaged in the field, then the Z-plane of the adaptor must be exact. If a fan blade weighs 35 pounds, the desired unbalance tolerance is 0.5 oz-inch and 30% of the measurement error is allotted to adaptor radius, then the adaptor contact radius must be machined to a tolerance of 0.000,300 inch. We have found that few manufacturers of blade adaptors realize the required tolerance, or are capable of achieving it. The result is a large variation in measured moment between different moment weight measuring facilities.

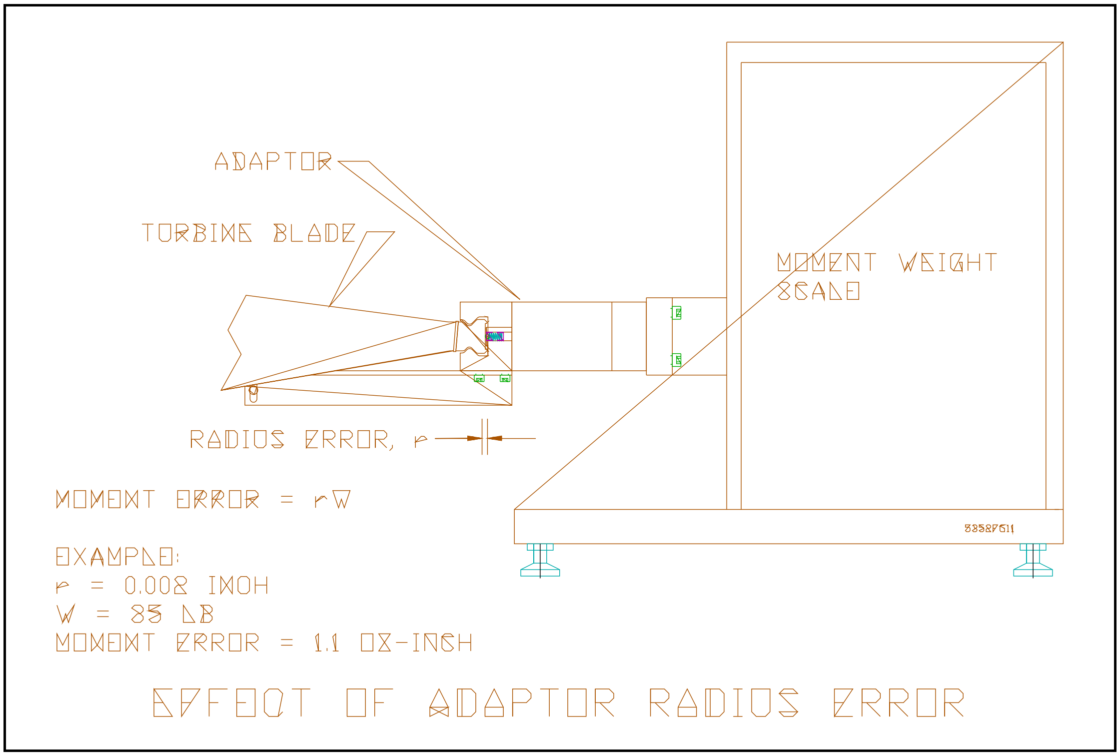


Figure 10

4.3 Rotor hub dimensional accuracy limits There is no guarantee that a stage will be balanced after matched pair of blades with equal moment weight are installed if the diameter of the dovetail (or other root shape) in the rotor hub is not held to a close tolerance. If a fan blade weighs 35 pounds, and the desired unbalance tolerance is 0.05 oz-inch, then the hub must be machined so that the Z-plane radius is held to a tolerance of 0.001 inch. This is difficult to do, but the added cost may be less than the cost of increased problems in balancing if this tolerance is not maintained. We have seen tolerances on engine drawings which would indicate that a 0.008 inch variation in radius was acceptable. We're told that the hubs are actually much better than this, so the problem is not as large as the drawing would indicate they might be. If that's the case, then why not revise the drawings, so a bad hub will be rejected?

Rotor hub runout does not affect the concept of blade replacement in the field, since the rotor originally has been spin balanced before assembly in the engine. As long as the blade replacement has the same moment as the original, then the balance is retained, even if the hub diameter is not closely controlled (see cautionary note on page 14).

4.4 Adaptor Repeatability The adaptor must hold the blade consistently in the same position, and this position must simulate the actual position in the turbine rotor. To determine adaptor repeatability, measure the same blade 10 times, making certain to remove and reinstall the blade in the adaptor before each measurement. It is a good idea to allow several operators to measure a master blade when you are determining repeatability, since the operator may be unconsciously influencing the moment reading by installing the blade in the adaptor in a specific way. If you do not have a rest stop to hold the blade in position during measurement, then you should force the blade to one side or the other before clamping it to determine the uncertainty due to blade lean in the adaptor. The most common adaptor problems are:

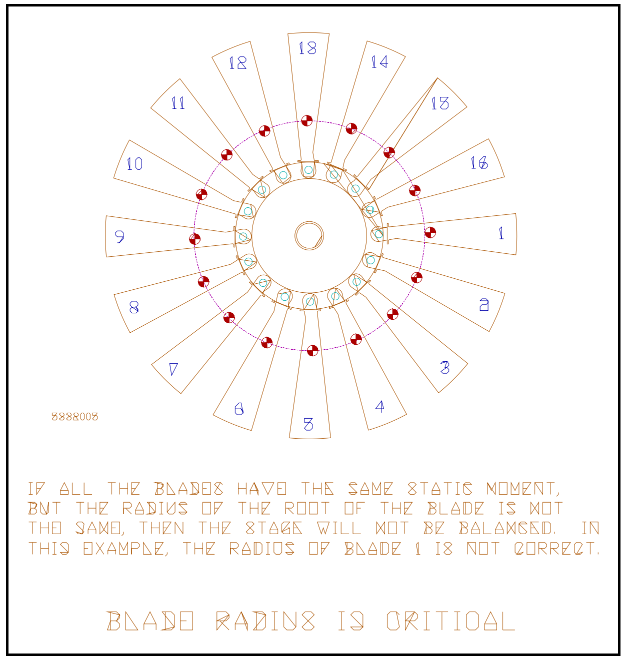


Figure 11

4.4.1 The blade is not properly aligned in the adaptor. The measurement axis of the machine should pass through the CG of the blade. If the blade is cocked in the adaptor, then blade will not contact the adaptor at the same point as it contacts the rotor hub in the engine, and the radial moment will be in error. If you are measuring 3 axis moments, then there will be a large error in tangential moment. The solution to this problem is to use a rest stop bar, or to use gravity to align the blade. These techniques are described in more detail in a later section of this paper.

4.4.2 The adaptor is not properly designed. The adaptor should force the blade forward in a manner which simulates centrifugal force. If the adaptor is designed so it forces the blade backwards, then moment weight measurements are referenced to the wrong surface. Another bad adaptor design is to lay one side of the dovetail in a vee groove.

4.5 Alignment of turbine blade in an engine When a blade is installed in a rotor and spun up to speed, a centrifugal force of thousands of pounds acts radially through the CG of the blade. In the example illustrated in Appendix A of this paper, this force is 133,000 pounds! During acceleration of the rotor, there is considerable vibration. This helps to seat the blades in a stable orientation.

4.5.1 Radial alignment The centrifugal force pulls the blade root tightly against the contact surface of the rotor hub. Therefore, the radius of the Z-plane in the hub defines the radius of a particular blade. The Z-plane radius of each blade will differ slightly, due to machining error.

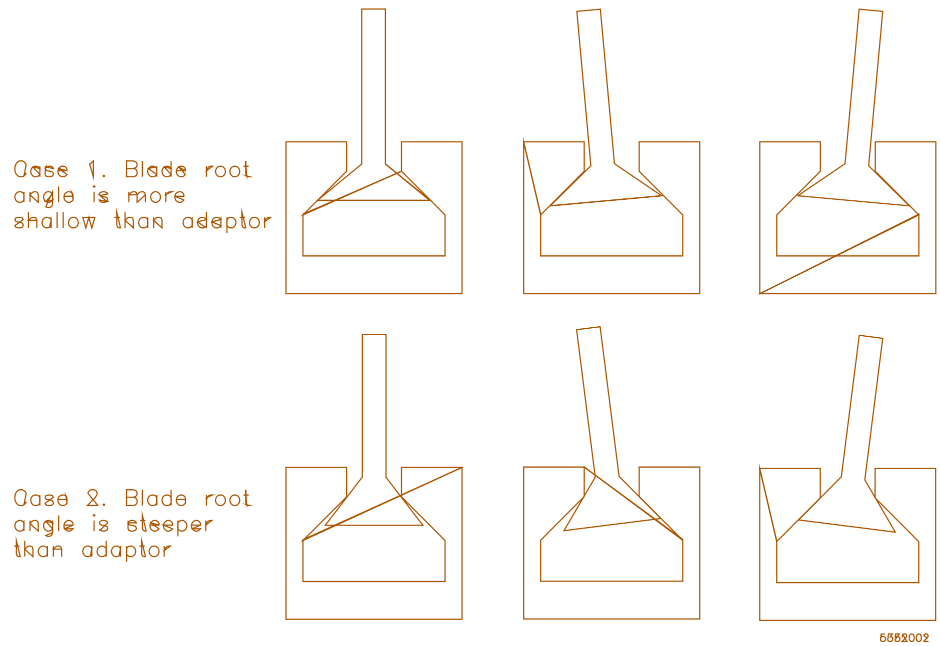
4.5.2 Axial/tangential alignment The centrifugal force acts radially through the CG of the blade, causing the CG to align itself transversely with the effective center of the attachment point of the blade. The blade twists in the hub to permit the CG alignment. Generally there is enough play between blade and hub to prevent any serious distortion at the blade root. Note that the shape and perpendicularity of the slot in the hub defines the axial position of the blade. The tangential position is determined by the relationship between blade CG and the effective center of rotation of the blade in the slot.

4.6 Alignment of turbine blade in a moment weight scale The adaptor should simulate the rotor hub and hold the blade at the same orientation as it has in the engine. If the blade contacts the adaptor at a different root location than it does in the hub in the engine, then the measured radial moment will not be a valid prediction of unbalance in the rotor. A mechanism in the adaptor must force the blade forward against the mating surface of the adaptor to simulate the centrifugal force in the engine (but it is not necessary for the force to be as large as it is in the engine).

The blade must be seated in the adaptor in the same manner as it will be when the engine is rotating. This is particularly important when measuring 3 axis moments on large fan blades. If you do not fixture the turbine blade in a moment weight scale so its CG is within a few thousandths of an inch of the location it will be in the engine, then the transverse moment measurements (axial & tangential) will be of little value in predicting unbalance of an assembled rotor. In order to do this, you must have a means of detecting blade CG location.

4.7 Don't rely on the adaptor or its clamping mechanism to align the blade CG. Because of all the possible deviations of the contact surfaces of the blade root, it is not realistic to attempt to use the fit between blade and adaptor to align the blade during moment measurement. The adaptor can be used to define the radius of the blade (this is what happens in the engine), but it cannot be used to define the tilt of the blade.

There is a common misconception that you can force a blade to orient itself correctly in the adaptor by applying a large clamping force (such as can be obtained with a hydraulic cylinder). This might be true if the fit between blade and adaptor were perfect. However, even the smallest error in blade root angle will cause an uncertainty in blade position. Figure 12 shows what happens when the angle of the contact surface of the blade differs from the angle in the adaptor. If the blade root angle is smaller or larger than the adaptor, then the adaptor is capable of clamping the blade in a number of positions. There is sufficient friction at the contact surfaces so that the blade will usually remain wherever it was located when the clamping pressure was applied. The friction force increase is proportional to the clamping force, so that increasing the clamping force will not serve to overcome this friction and align the blade.



Exaggerated illustration of blade position uncertainty in adaptor

Figure 12

Note: The discussion above assumes that the only error in blade shape will be the deviation of the angle of the blade root relative to the tangential axis of the blade. Actually, the real situation is much worse. There are many additional deviations which can exist: in addition to deviation from the correct angle, the two contact surfaces of the blade root may converge, and either or both surfaces can be convex or concave. All of these errors will increase the uncertainty of the blade location when clamped in the adaptor.

Another misconception is that a flat clamp on the inboard end of the blade can be used to align blade CG. The inboard end of a blade will not necessarily be exactly perpendicular to the axis of the blade, nor is it necessarily exactly flat, so its surface cannot be used to define the correct blade orientation. Because the width of the inboard end is very narrow relative to blade length, a small angle error translates into a large error in blade CG position.

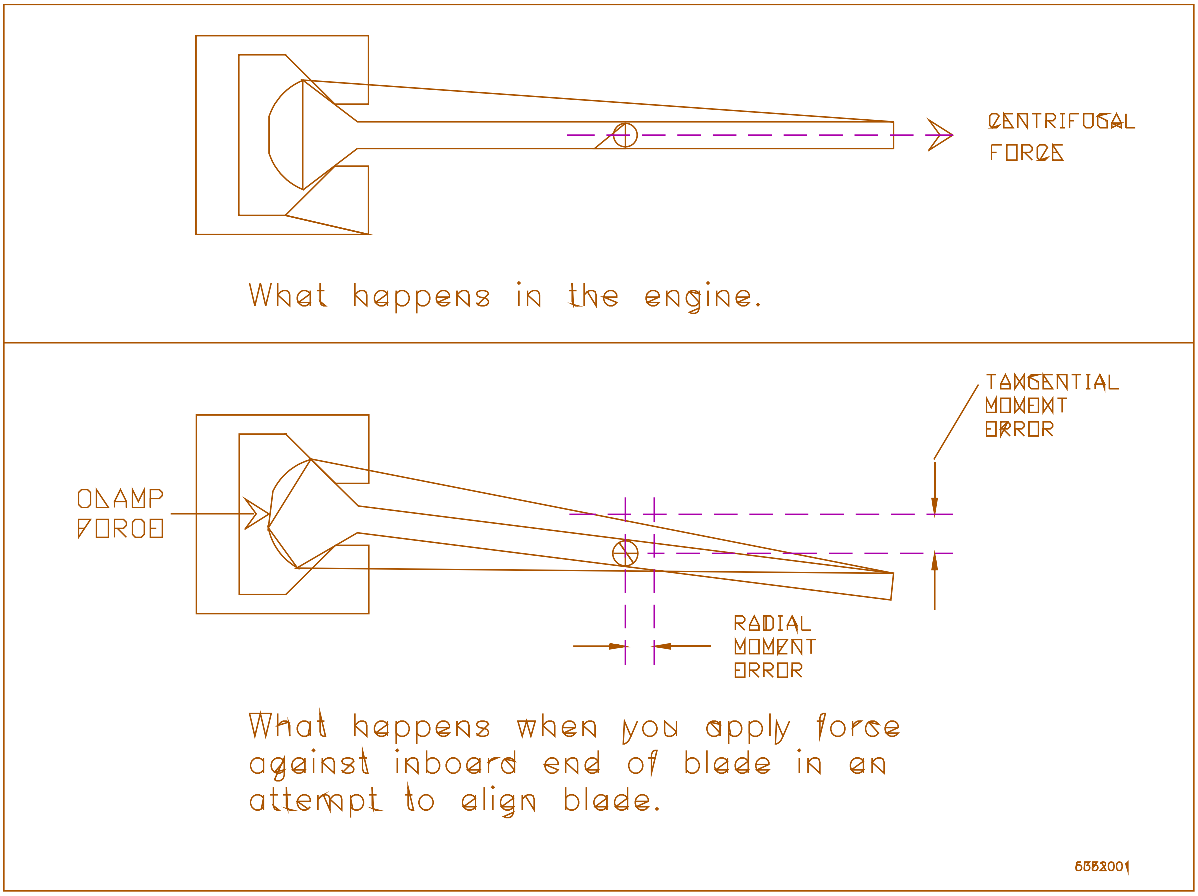


Figure 13

4.7.1 Using a rest stop to align blade CG In some cases, a support can be used to contact the blade about 2/3 of the distance from the root. This method is often suitable for single axis moment measurements, but is not adequate for three axis measurements, since the contour of the blade usually exhibits considerable variation and bears no specific relation to blade CG.

4.7.2 Using gravity to align the blade CG The best way to align a blade relative to its CG is to make use of the force of gravity to align the blade. If the blade is clamped in the adaptor while it is hanging in the adaptor, then it will automatically be aligned relative to its CG. This will simulate the true orientation of the blade in the engine.

Here are three concepts for rotating the fan blades to a vertical position before clamping. Each method positions the blade so its CG is coincident with the measurement axis of the moment weight scale.

Method 1 = 90º Machine Tilt This method requires a specially designed moment weight machine. The entire moment weight machine is rotated 90º so that the blade adaptor faces downward. This permits the blade to be oriented so that its CG is in line with the measurement axis. The adaptor is then clamped in this position and the machine is rotated back to its horizontal position for moment measurement. In order for this concept to work, the moment weight scale has to have a rotation device which returns the moment scale to a precise level condition. The scale must be designed to permit the machine to be tipped without damage to the mechanism or alteration of its calibration. This is the most likely method to be successful, since the fixture is rigid and unaltered during the clamping operation.

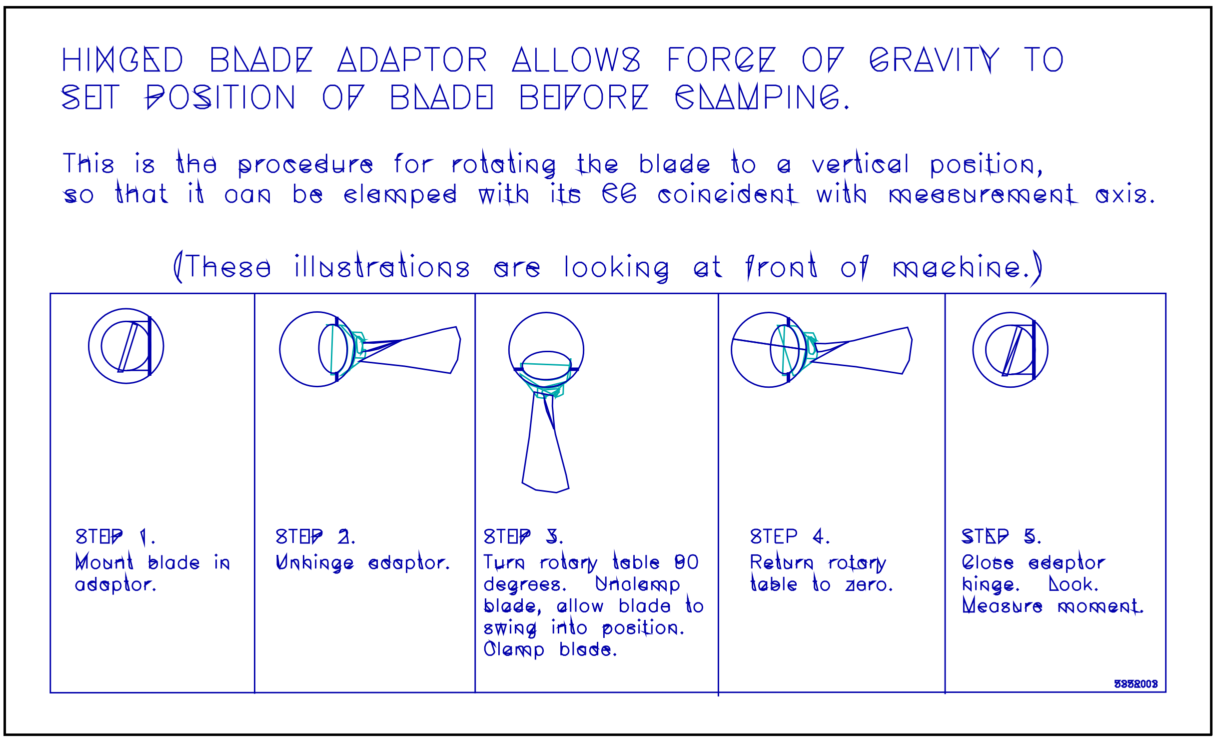


Figure 14

Method 2 = Hinged Adaptor An adaptor can be constructed which is hinged to allow the blade to be rotated 90º to the right (facing machine). The enclosed illustration shows the steps in using this concept. The rotary table on the machine is used to swing the blade to a vertical position. The blade is unclamped, allowed to settle into alignment, and re-clamped. This method has some risk, since the hinge mechanism has to return to exactly the same position each time. A very rigid repeatable clamp is required to hold the hinge closed during moment measurement. For a 35 pound blade, a shift of the blade CG of 0.001 inch will cause a 0.5 oz-inch moment error. Since the distance from adaptor to blade CG is greater than the stance of the adaptor clamp, the clamping error is magnified. To stay within a 0.5 oz-inch limit, the clamping repeatability should be 0.0003 inch or better.

Method 3 = Hanging the adaptor The least expensive (and most awkward) solution is to mount the blade in the adaptor, then remove the adaptor and blade, hang the adaptor and blade so it is vertical, re-clamp the blade, and then reinstall the adaptor and blade on the machine. This method requires a fast acting clamp on the moment weight scale to permit quick removal of the adaptor. The clamp must be repeatable within 0.0005 inch. The big problem is the handling of the heavy adaptor plus the blade (which can weigh up to 40 pounds). This method is the most prone to error and includes the risk of damaging the blade or injuring the operator during the loading and unloading of the heavy adaptor and blade. There is a considerable chance of disturbing the alignment of the blade during loading.

All of these methods assume that the force of gravity will cause the blade to rotate into the correct position, and that the adaptor design is such that it does not disturb this blade alignment during the clamping operation.

NOTE: The process of using gravity to align the blade CG prior to clamping the blade in the adaptor is proprietary to Space Electronics. I am in the process of applying for a patent on this concept.

4.8 Moment shift due to clamping mechanism A very common mistake in adaptor design is to use a clamping mechanism whose mass moves in the direction of measurement. This results in a built-in radial moment error. For example, if the clamping mechanism consists of a hydraulic cylinder and pressure plate whose mass is 4 oz, and the mechanism has a travel of 0.5 inch in the radial direction, then this clamping mechanism produces an error of 2 oz-inch. This error is easy to measure: first measure the moment with the clamp retracted, and then remeasure with it extended (but no blade in place). Any difference is due to clamp mass.

When comparative measurements are made with a master blade, then this error is reduced to the difference between the clamp moment when measuring the master blade versus the clamp moment when measuring a production blade. Since the rear face of a blade is not held to a tight tolerance, this can still be a significant error.

Space Electronics manufactures adaptors with clamping mechanisms that do not result in a moment shift. This is accomplished by using a mechanism which simultaneously moves two masses in opposite directions. Another advantage of our clamping mechanism is that it remains parallel for all positions. In contrast, clamps with a multitude of cylinders can cock to one side (the cylinder with the least resistance moves forward first; when it encounters resistance, then the other cylinders "catch up").

5.0 Conclusion

Appendix A: Calculation of Centrifugal Force on Blade

Blade assumptions:

Blade Weight	W = 35 lb
Z plane radius	Z = 15.5 inch
CG radial offset from Z plane	C = 18 inch
CG radius	R = 33.5 inch
Engine speed	S = 2000 rpm

Centrifugal force (F) :

Appendix B: Adaptor Accuracy Required

Blade assumptions:

Blade Weight	W = 35 lb
Moment accuracy required	E = 0.5 oz-inch
Percent allotted for measurement error	33 %

Adaptor accuracy (A) required:

$$\frac{(0.33)(0.5)}{(35)(16)} = A = 0.000{,}295 \text{ inch}$$

The adaptor must hold the blade to its true position within a tolerance of 295 millionths of an inch!

ABOUT THE AUTHOR

Richard Boynton is President of Space Electronics, Inc., Berlin, Connecticut, a company he founded in 1959. Space Electronics, Inc. manufactures instruments to measure moment of inertia, center of gravity, and product of inertia. Mr Boynton holds a B.E. degree in Electrical Engineering from Yale University and has completed graduate studies in Mechanical Engineering at Yale and M.I.T. He is the author of over 66 papers, including 30 papers presented at SAWE conferences. He is the author of the SAWE Recommended Practice for Standard Coordinate Systems for Reporting the Mass Properties of Flight Vehicles. Mr. Boynton has been a member of SAWE for 29 years and is currently Director of the Boston Chapter. In 1992 he was elected a Fellow of the SAWE. He has designed many of the mass properties measuring instruments manufactured by Space Electronics. Also, Mr. Boynton is the Chief Executive Officer of Mass Properties Engineering Corporation and is a professional folksinger.