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A New Moment Balance Machine for Turbine Blade Measurement

by

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Abstract Balance is a major factor in determining the reliability and service life of turbine rotors used in jet engines or power plants. The task of balancing a completed rotor can be greatly simplified if the individual blades are first measured and sorted according to static unbalance moment. They are then assembled in the rotor in such a way as to compensate for hub unbalance, resulting in an assembly that is approximately balanced. Final balance is then done on a horizontal spin balance machine.

Space Electronics has designed a special static balance machine to measure turbine blade moment. Previously this task has been accomplished using knife edge and load cell technology that was developed in the 1950's. Our machine combines force rebalance with flexure pivots to result in sensitivity and accuracy that is at least 20 times better than the existing state of the art.

This paper discusses the various steps in the process of balancing a turbine rotor. The new Space Electronics machine is described in detail. Fixturing is a limiting factor in blade moment measurement. We discuss some of the problems and propose some novel solutions.

Introduction Jet engine gas turbine rotors turn at speeds greater than 7000 RPM. Some smaller diameter turbines reach speeds as high as 30,000 RPM. Even a small unbalance will greatly reduce the number of hours the engine can run before overhaul. An analysis of the unbalance forces will quickly explain why. The magnitude of the horizontal force is:

$$\text{Centrifugal Force (lbs) } F_1 = M_1 \; x \; R_1 \; x \; S^2$$

where M_1 = mass of unbalance in slugs
R_1 = radius of CG of unbalance in feet
S = speed in radians per second

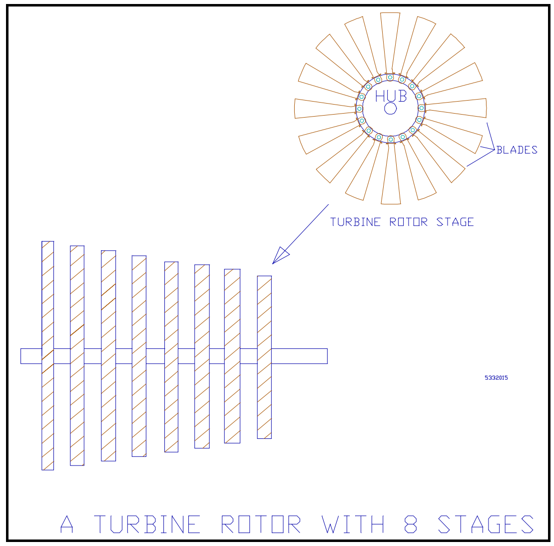
Converting the mass into weight and the speed into RPM:

$$\text{Centrifugal Force (lbs) } F_1 = \frac{W_1 \; x \; R_1 \; x \; (RPM)^2}{35{,}207}$$

where W_1 = weight of unbalance mass in lbs
R_1 = radius of CG of unbalance in inches
RPM = speed in RPM
35,207 = constant to transform units

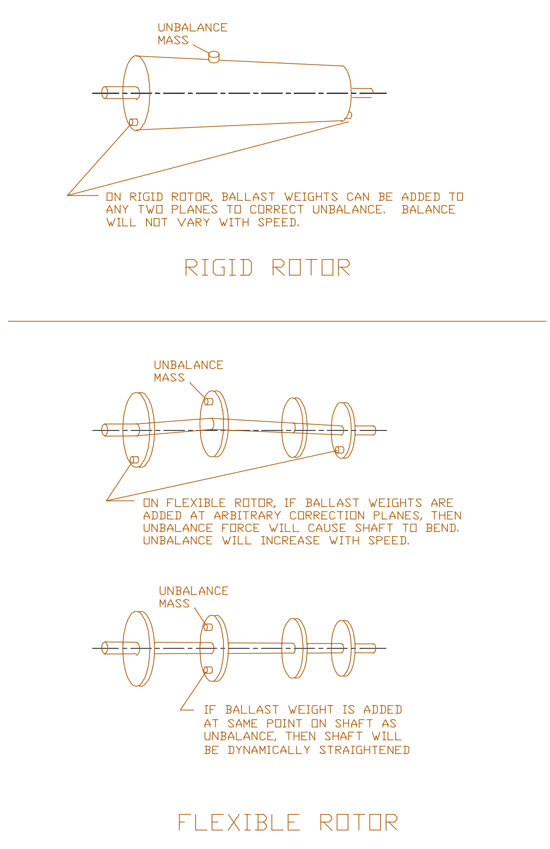
If a stage in the rotor has a weight of 500 pounds, and a CG offset of 0.001 inch, then the resulting unbalance force at 12,000 RPM is 2045 pounds. This is a vibratory force, which would quickly deteriorate the bearings.

Elements of a gas turbine rotor Figure 1 shows a cross section of a typical jet engine rotor. This engine consists of a single shaft with a number of fans attached to it. Each fan consists of a hub with a set of blades extending radially outward from the hub. The blades are machined out of exotic materials to be able to withstand the forces at a temperature which can be greater than 1200^{o} f. The blades are often flexibly mounted. They do not maintain their operating position unless the rotor is spinning at high speed, so that centrifugal force overcomes the force of gravity. These fans are known as "stages" in the jet engine. These stages are assembled to the shaft using extremely tight tolerances.



A TURBINE ROTOR WITH 8 STAGES

Balancing a jet engine rotor If the rotor were entirely rigid, then its unbalance could be corrected by spinning the rotor, measuring the CG offset and product of inertia, and then adding a correction weight at each of two planes to compensate for the unbalance. In practice this does not work. The shaft is small in diameter relative to the unbalance forces, so that it will bend when it spun at a high speed. The measured unbalance will increase as the speed is increased, because the bending of the shaft will cause the CG offset to increase. This means that the ballast corrections must be made at a location along the shaft that corresponds to the source of the unbalance. This type of correction falls into the category known as "flexible rotor balancing". For this reason, gas turbine rotors are among the most difficult objects to balance.

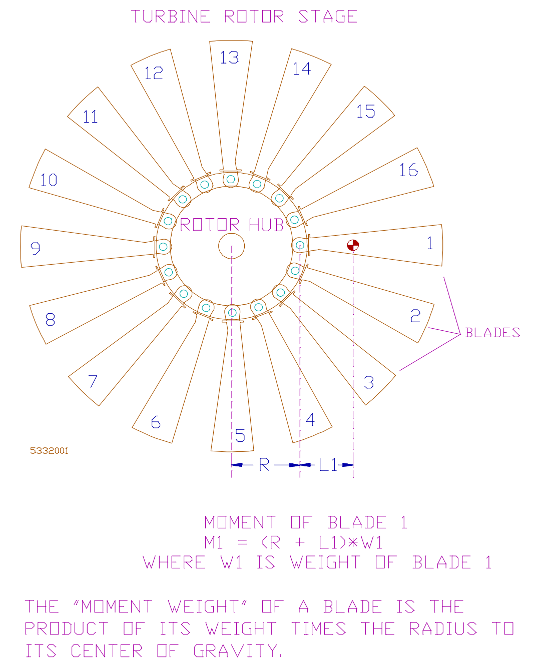


The solution to the problem is to balance each stage separately before assembling it in the rotor. The task of balancing each stage can be simplified if the blades are assembled in the hub at a location that results in the smallest initial unbalance. There are two ways of sorting the blades: by weight or by moment. Moment sorting results in the best balance, but it requires a special machine to measure the moment.

Sorting blades by static moment Normally, solid rotors such as flywheels are balanced by adding or removing metal at two balance planes. This is not possible with a turbine stage, since the solid hub is very small relative to the diameter of the blades. You cannot correct the blades themselves, since any alteration would reduce their strength and aerodynamic performance. The solution is to measure the static unbalance moment due to each blade and then sort them in the optimum order on the hub, so that unbalance is reduced to a minimum.

"Pan weighing" the blades More than 30 years ago, it was recognized that blades could be sorted by weighing them and then placing them in the rotor so that blades of equal weight were opposite each other. This method is still used if the blades are small and light relative to the hub, so that their contribution to unbalance is small.

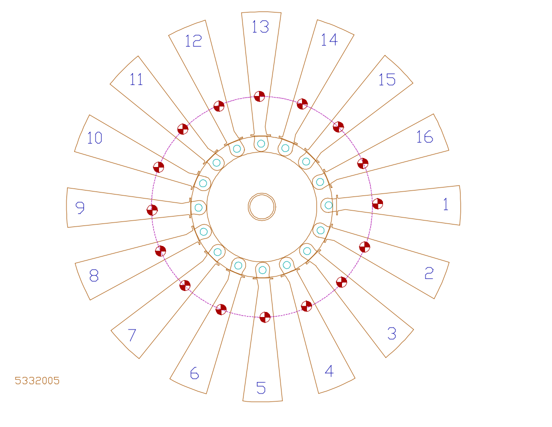
"Moment Weighing" the blades A more accurate balance can be obtained by sorting the blades so that blades of equal static moment are opposite each other. Static moment is the product of the weight of the blade times the distance from the center of rotation to the center of gravity of the blade. This static moment is sometimes called "moment weight", and the machines to measure it are called "moment weighing machines". If you started with a balanced hub, and then assembled the blades so that the moment weight of one blade was identical to the moment weight of the blade 180° away, then the rotor would be very close to a perfect balance. In actual practice, the rotor hub is rarely exactly balanced, and it is often impossible to find pairs of blades with exactly the same static moment, so a more sophisticated solution is necessary to achieve the best balance. In this case, specialized software is used which selects the blade locations so that the unbalance of the rotor disc is compensated for by an equal and opposite net unbalance in the blades. The larger the quantity of blades available, the better chance there will be that the solution calculated by the computer will achieve the balancing tolerance for the assembled rotor.



DEFINITION OF "MOMENT WEIGHT"

The radius of the blade in the engine is critical The hub in the engine must be machined very accurately, or the process of moment sorting will not necessarily yield a balanced stage. The concept of sorting by static moment is only valid if the radius of each blade is identical in the engine. Even a difference of 100 millionths of an inch will result in an unbalance which can be measured on a Space Electronics blade balance machine. Since it would be impossible to machine a hub to this accuracy, some compromise is necessary. This means that the optimum distribution of the blades which was determined by the computer may not yield the lowest unbalance. Some swapping of blades may be necessary.

Spin balancing each stage After the stage has been assembled with the blades in the optimum order, it is mounted on a single plane spin balance machine to verify balance. Theoretically, the stage should be in balance without adjustment if hub unbalance was correctly measured, and if the radius of hub attachment was the same for all blades. However, if the hub has slight differences in radius at the different blade mounting points, then there will be an unbalance even though the blades were installed in the correct order. Small corrections can be made to the hub if the unbalance exceeds a specified tolerance. If there is not enough correction available on the hub, it is possible to swap blades, using the moment weight data as a guide.



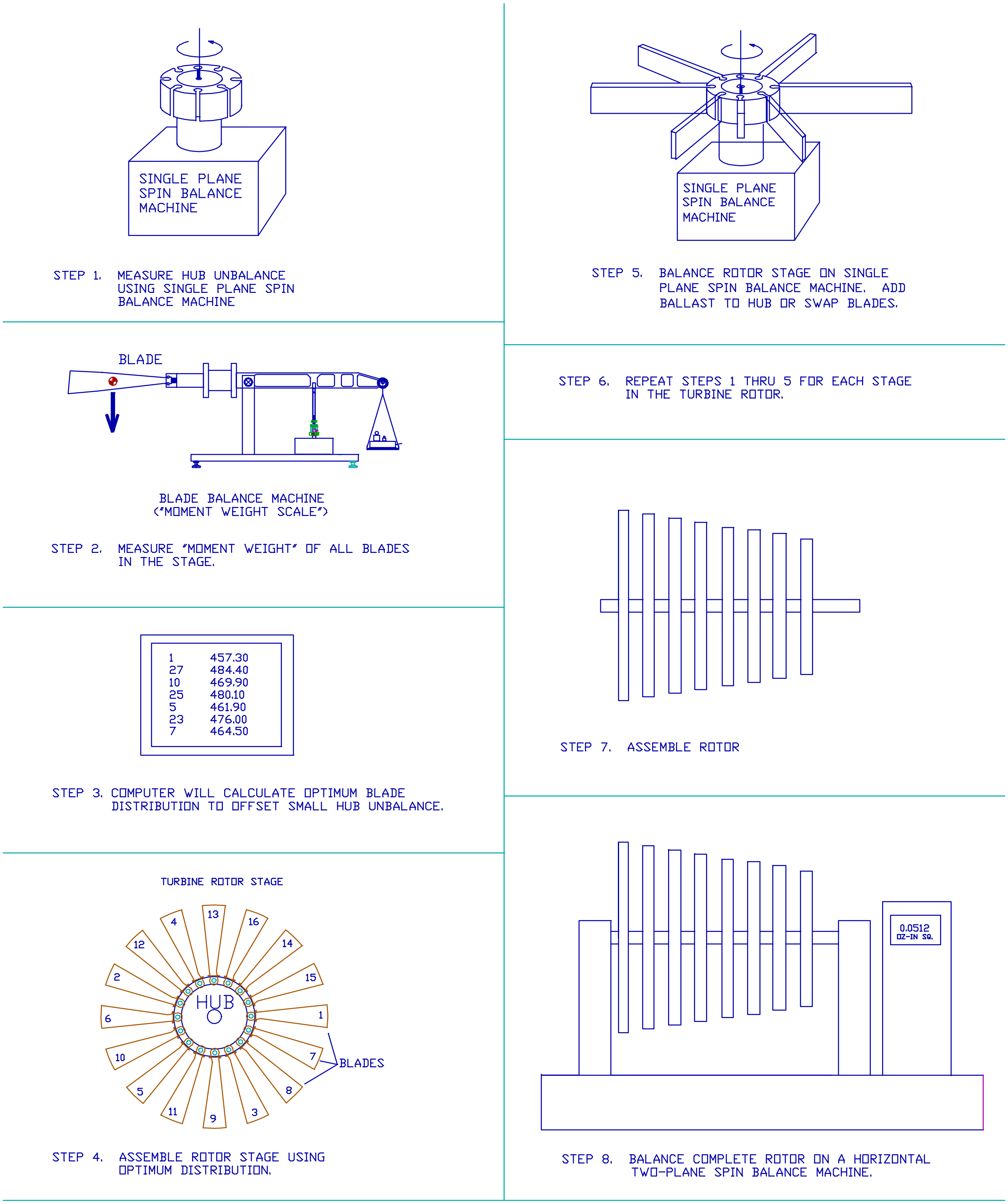
BLADE RADIUS IS CRITICAL

The fit on the balancing machine shaft must be almost perfect for this spin balance measurement to be valid. One successful technique is to use an expandable chuck consisting of a hollow shaft which is 0.0002 inch smaller than the bore of the stage. This shaft is filled with hydraulic fluid; by turning a threaded piston, hydraulic pressure expands the shaft.

A single plane balancing machine can be used because the stage is very narrow relative to its diameter, and because the blades are flexibly mounted, so that they automatically line up with their CG in a single plane, even if the hub is slightly cocked on the shaft.

If you used a horizontal balancing machine to make this measurement, the flexible mounting of the blades on the hub would cause a problem when attempting to balance at a slower speed than the operating speed: the blades would flop from side to side as the stage rotates in the balancing machine. This effect is minimized by using a balancing machine with a vertical shaft, so that the stage is horizontal when spinning.
Another potential problem is windage. If the stage was not shrouded during spin, an enormous blast of air would come out of the centrifugal fan. Furthermore, air turbulence

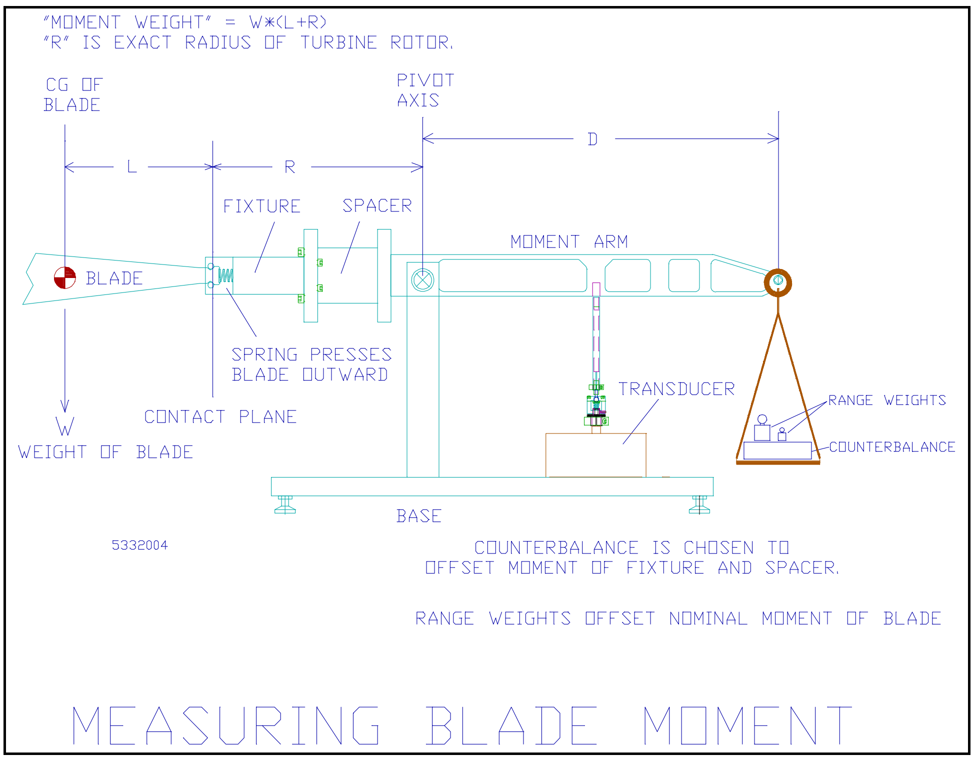
would introduce forces which could obscure the forces due to unbalance. The solution is to use a heavy metal cylindrical shroud which surrounds the stage during spin. The shroud provides protection to the machine operator if a particle of metal was ejected from the spinning stage. The shroud fits tightly around the stage so air cannot be drawn in. This greatly reduces the amount of work done by the fan, and hence the amount of power required to accelerate the fan up to speed. (If you have used a vacuum cleaner, you already know about this effect. When you block off the suction tube, the vacuum motor speeds up rather than stalling, indicating that it is using less power). And finally, turbulence is reduced because the air travels in a smooth circular path. Some operators also rotate the fan backwards when balancing, to further reduce turbulence.



THE 8 STEPS TO TURBINE ROTOR BALANCE

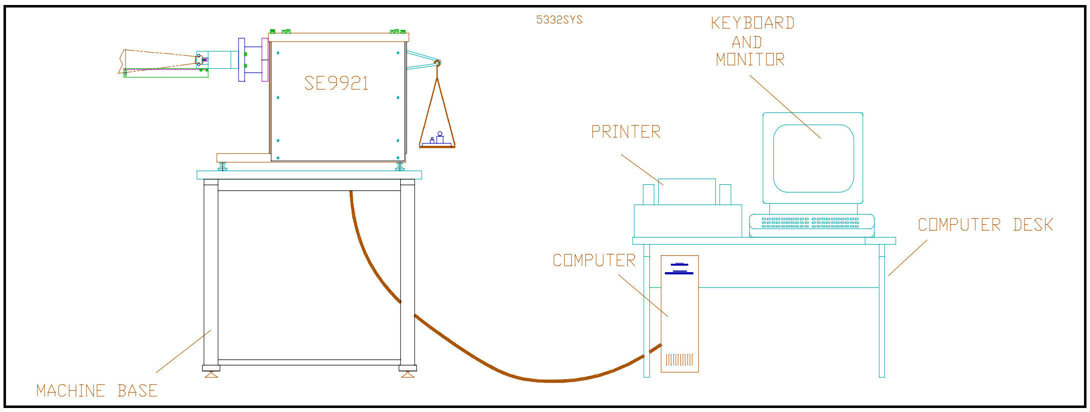
Two plane balancing of completed rotor When all the stages have been individually balanced, they are assembled on the shaft, and the entire assembly is placed on a horizontal two plane balancing machine. It is necessary for the machine to be horizontal, since both ends of the shaft must be supported. This step in intended as a final check. If all the stages are correctly balanced, there should be no need for further correction when they are assembled on the shaft. Excessive unbalance will primarily be due to slight errors in centering of the fan stages (or more specifically, differences in fit between the single plane balancing machine which was used to balance each stage and the rotor). This test has a minimum fixturing error since the rotor turns on its own shaft, but even greater accuracy may be possible if rotor turns in the bearings which will be used in the gas turbine. If the rotor unbalance is outside the specified tolerance, minor correction can be made for unbalance at the ends of the rotor.

Description of Space Electronics Moment Weight Machines Moment Weighing Machines such as the Space Electronics Model SE9921 are specifically designed to measure the "moment weight" of jet engine blades. These specialized static center of gravity instruments have extraordinary moment sensitivity and can detect changes as small as 0.001 oz-inch. The blade is mounted horizontally on one side of the machine and a counterweight is mounted on the other side. The counterweight offsets the nominal moment of a blade and its holding fixture. The machine then determines the deviation in moment weight from the nominal for the blade being measured.



On-line computer The machine is interfaced to a computer. The blade moment is displayed on a digital readout on the computer CRT. The computer is used to store the data, and print the data. After a number of blades have been measured, the operator enters the unbalance of the rotor hub, and the computer then selects the specific blade for each location to achieve optimum balance. The computer also tells the operator how to run the machine, using a step by step procedure. All operations are menu driven with user friendly instructions. The keyboard is used for operator entries. Reports are automatically generated on the printer.

A specific fixture is required for each blade to be measured. Another major feature of the computer is that it chooses the fixture from the data stored on the hard disc with the blade part number. The computer also specified the nominal blade moment, and the range weights required. Relatively unskilled operators can be used because all this information is automatically loaded into the system when the operator enters the blade part number.



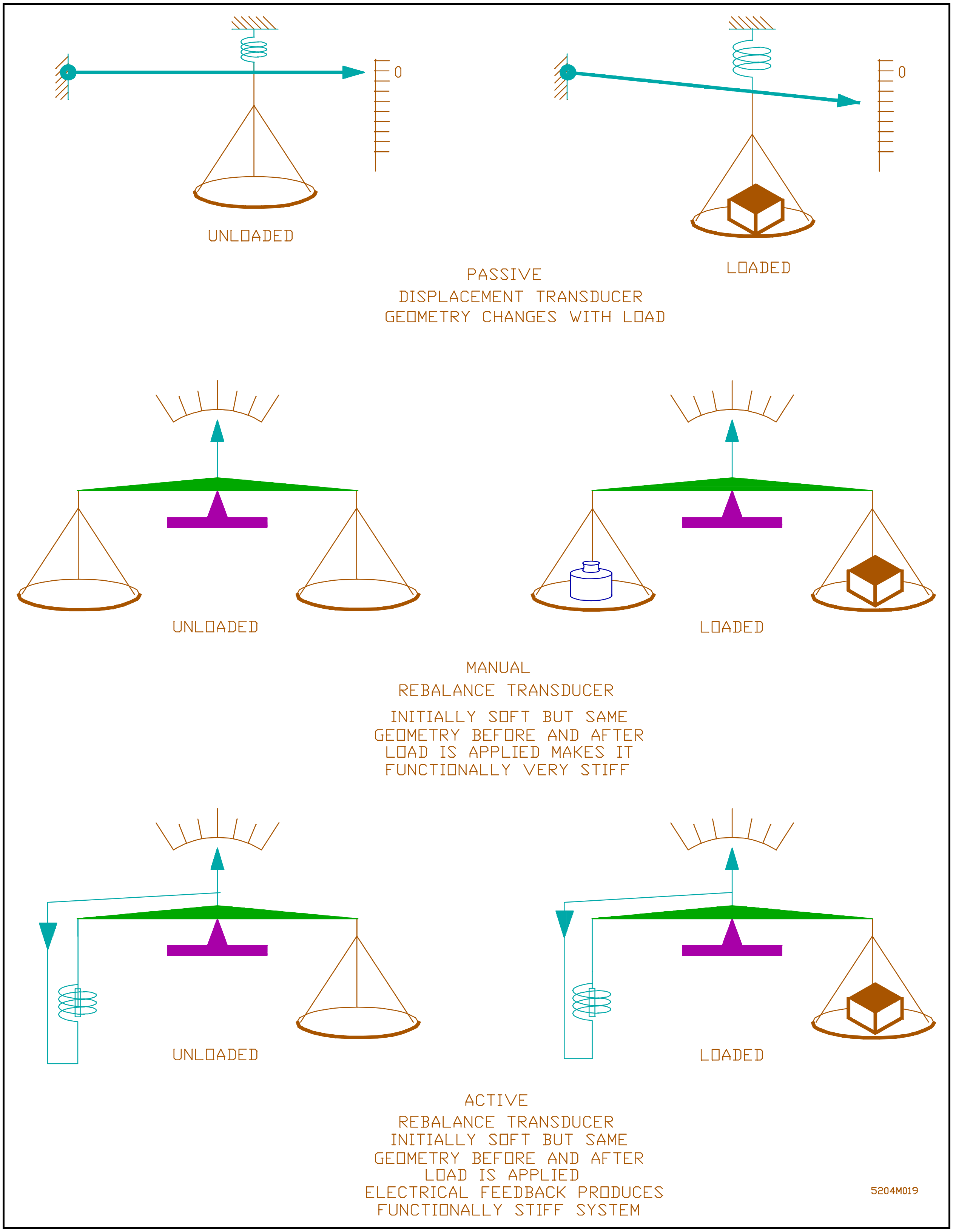
Instrument Specifications These instruments are available in several operating capacities. Typical specifications for two instruments are:

Space Electronics MODEL	MAXIMUM MOMENT (oz-in)	INDICATOR RANGE (oz-in)	ACCURACY % + (oz-in)	INDICATOR RESOLUTION (oz-in)	INTERFACE RADIUS* (inch)
SE9921A	1000	100	.04% + .001	.0005	2
SE9921B	8000	1000	.04% + .01	.005	5

Pivot axis uses crossed-web flexures Traditionally, moment weight machines have used knife edges to form the pivot axis. These have the disadvantage that they are subject to wear and damage. Furthermore, unless the knives are aligned perfectly, there is a built-in error in the axis location and some friction results, limiting the sensitivity. We use 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 two strips of spring steel oriented at right angles. There is only one point where the combination of these two strips can bend. Since there is no relative motion, there is no friction. There is no surface to wear.

Force rebalance technology Our blade balance machines use the same type of force rebalance technology as our KSR series mass properties machines. Rather than using strain gages to measure the unbalance torque on the beam, we apply an equal and opposite 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.

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. The Space Electronics machine incorporates electronic damping in the force rebalance transducer. This accomplishes the same task as the oil dashpot, but has none of the disadvantages.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GEOMETRY BEFORE AND AFTER
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ELECTRICAL FEEDBACK PRODUCES
FUNCTIONALLY STIFF SYSTEM
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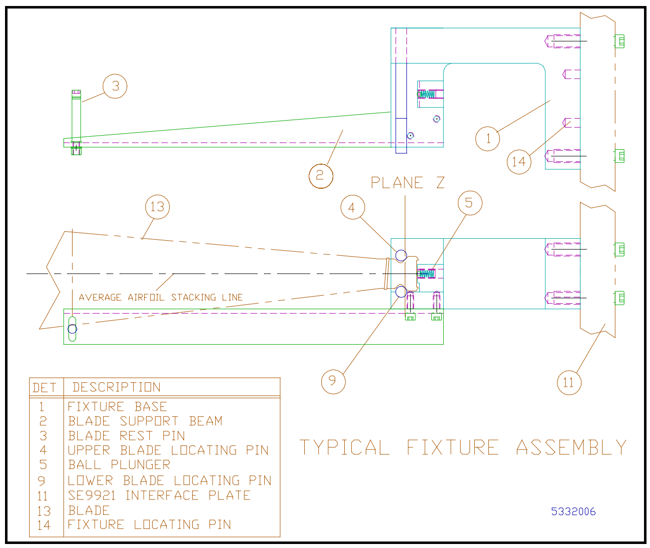
Location of Machine Any high accuracy mechanical device can only achieve its full potential if certain environmental factors are controlled. This machine should be located on a rigid bench which is shielded from drafts and rapid temperature changes. External vibration will adversely affect performance.

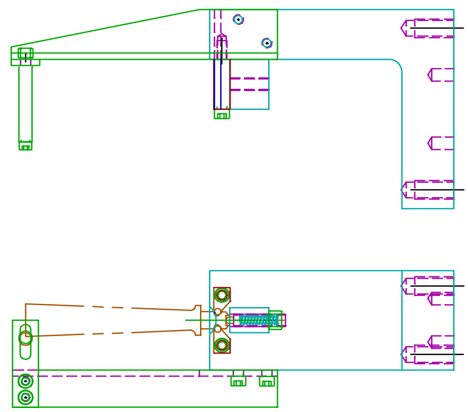
Fixtures A fixture is required to attach the blade to the moment scale, and to place the blade at a specific distance from the pivot of the balance beam. This simulates its radial position in the engine by placing its center of gravity (CG) at the same distance from the pivot as it would be from the engine centerline. If this fixture duplicates the shape of the rotor attachment, then dimensional variations at the root of the blade do not introduce a balancing error. Most fixtures are custom designed for a particular blade, but there are also various kinds of universal fixtures. These fixtures have calibrated adjustments for blade radius and root depth. Adaptor tooling is used to mate these fixtures to a specific blade.

A typical fixture assembly and mounted blade is shown in figure 14. The blade is located by means of pins which contact the blade at the reference (Z) plane. Firm contact with the pins is maintained by a spring plunger, which forces the blade outward to simulate the centrifugal force which is applied to the blades in the engine when spinning at high speed. The outboard end of the blade is supported on the blade rest pin.



Fixture counterbalance A counterbalance is added to offset the moment created by the fixture. In this way, the machine only measures the moment due to the blade. We use a simple concept in Space Electronics machines: all of our fixtures are designed to create the same moment. This means that only one counterbalance is required to correct for any of our fixtures. This counterbalance is removable, in case the operator wants to use a fixture made by some other firm (such as Pratt & Whitney). In this case, the operator can add weights until the fixture is balanced before measuring blade moment.

The radius of the blade in the machine is critical High sensitivity blade balance machines have a sensitivity better than 0.001 oz-inch. If the blade weighs 100 oz, then this sensitivity corresponds to a radius change of 10 millionths of an inch! It is impossible to achieve an absolute accuracy of 10 millionths, but the repeatability of comparative measurements approaches this, if the balance machine is shrouded to prevent drafts and the test area has adequate temperature control to minimize thermal expansion errors. As explained below. the use of a master blade eliminates the need to have a precise fixture radius.



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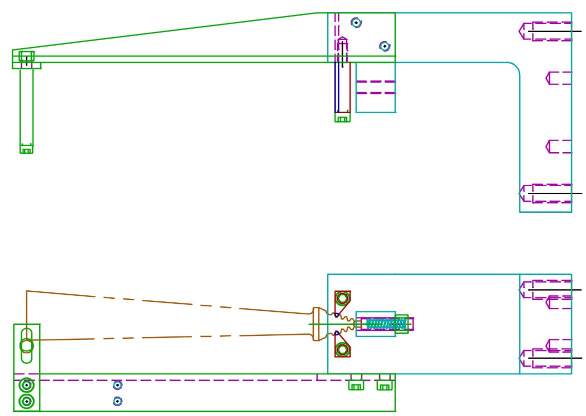

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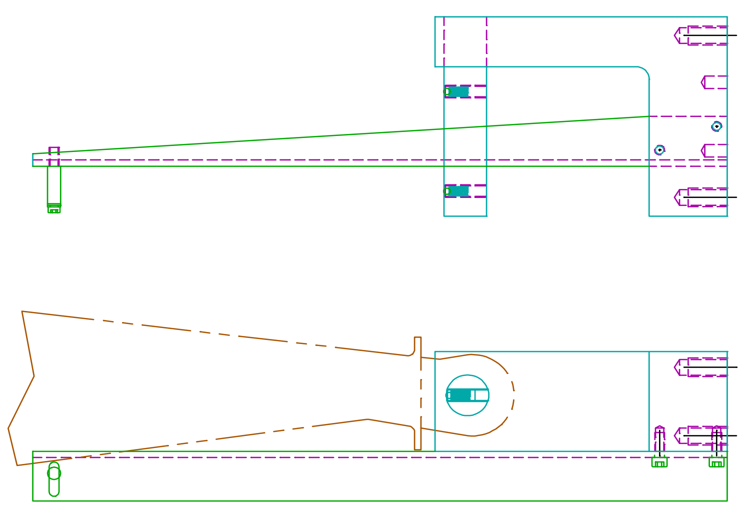

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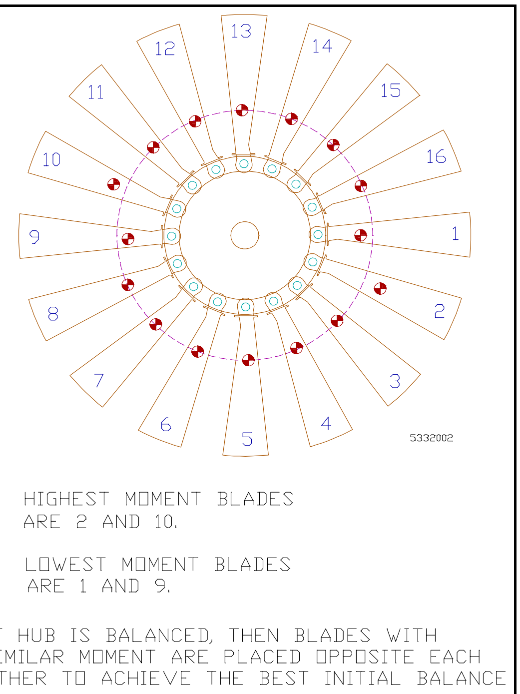
Relative vs absolute measurements If a set of blades are being sorted to achieve balance on a rebuilt engine, then it is only important that the measurement be relative. In other words, you are looking for the difference between blades. Since all measurements are made using the same setup, this will result in a balanced stage. However, if blades are being sorted for later use, and they may be combined with blades measured using other fixtures or moment weighing machines, then it is important the true moment value be measured. It is much more difficult to make an absolute measurement of blade moment than a relative measurement. The major source of error is the fixturing. The contact between the fixture and the blade will determine the absolute moment measurement accuracy.

Using a master blade A simple solution to this problem is to use a master blade. This is a blade which is usually very close to the nominal moment. This blade has been saved as a standard for moment measurement. The master blade is first inserted into the fixture, and counterbalance weights are added to the weight pan, so that the machine is approximately balanced. Then the machine is tared, setting the readout to zero. Subsequent blades are then measured. The readout indicates the deviation from the moment created by the master blade.

Measuring absolute moment If absolute moment values are required, then the fixture radius must be exact, and the moment readout must be of high precision. Our force rebalance technology allows us to detect moment change with an accuracy of one part in 300,000. The limiting factor will be fixture accuracy.



BLADE SELECTION CONCEPT

Sorting the blades by moment If you have a large number of blades, you may want to place the blades in bins according to their moment for easy retrieval when assembling the stage. Bins can be labelled according to moment, or they can be labelled with the Pratt & Whitney classification codes. Pratt & Whitney uses a letter designation to classify their blades (MM, MO, etc.).

Calculating optimum blade location There are a number of techniques which can be used to select the best location of the blades, so the stage will be as close to balance as possible.

Basic equal moment assembly The operator assembles the stage so that pairs of blades from the same bin are located opposite each other. This means that blades of equal moment are placed 180 degrees apart. In order for this to work, there has to be an even number of blades in the stage, so that all blades are directly opposite another blade. Jet engine manufacturers can use this method, because they have a large number of blades available, so that it will almost always be possible to find blades of equal static moment. This method cannot be used when rebuilding an engine, since there are only enough blades to fill a single stage.

Alternating high-low method This only works for stages whose total number of blades is divisible by 4. In this method, the blades are first sorted from the largest to the smallest moment. For example, if there were 8 blades, 1 would be the heaviest, and 8 the lightest. They are then arranged on the rotor:

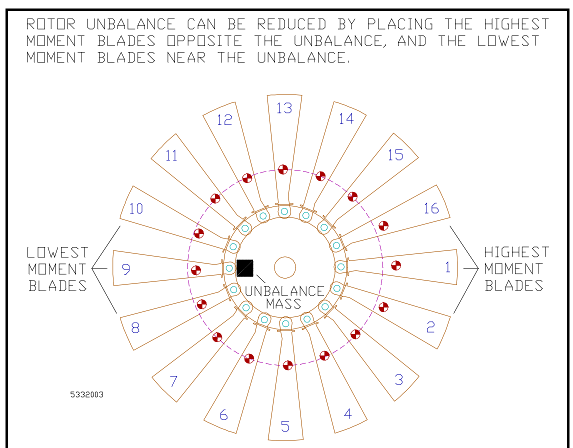
POSITION	1	2	3	4	5	6	7	8
BLADE NO. (1 Heaviest)	1	8	3	6	2	7	4	5

This arrangement has several advantages:

1. Heavy and light blades are alternated, so that the hub is not stretched into an egg shaped condition.

2. Blade 1 is slightly heavier than 2, but blade 8 is slightly lighter than 7, etc. If the distribution of moments is symmetrical, then this will result in surprisingly small unbalance. However, this method does not correct for any hub unbalance.

Best fit computer solution If you only have enough blades for a single stage, you should mark each blade with a serial number and its measured moment. The software will calculate the best blade to use in each position when the rotor is assembled. Theoretically it would be possible to simply program the computer to try all possible combinations, and choose the one that results in the lowest unbalance. However, even with modern high speed computers, this would require hours of computation time for a rotor with more than 30 blades. To shorten this time to a few seconds, Space Electronics has developed some very sophisticated algorithms to determine the optimum blade position. Unfortunately, we cannot disclose these in the paper, since they represent an investment of thousands of hours and our software represents part of the advantage of using our blade balance machines.



COMPENSATING FOR ROTOR HUB UNBALANCE

Conclusions Gas turbine rotors are among the most difficult items to balance. Assembling the turbine blades in an optimum configuration allows the operator to balance each stage, so that the flexible turbine rotor does not bend when rotated at a high speed.

ABOUT THE AUTHORS

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 60 papers, including 25 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 25 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.

Kurt Wiener is Chief Engineer of Space Electronics, Inc. Mr. Wiener holds a B.S. degree in Mechanical Engineering from M.I.T. and a M.S. degree in Industrial Education from Central Connecticut State University. He is a former Associate Professor of Mechanical Technology at Vermont Technical College. He is the co-author of 6 papers presented at SAWE conferences. His previous work includes machine and control system design and teaching these topics in industry. Kurt is the director and primary instructor for the well-known Space Electronics mass properties seminar which is taught several times a year.