CHAPTER 5

BALANCING

General

1. The high rotational speeds of the gas turbine engine make it essential that all rotating parts and assemblies are accurately balanced. Failure to achieve the correct balance, particularly of compressor and turbine rotor assemblies, will result in vibration and stresses to the engine, the intensity of which will depend upon the amount of *unbalance,* and the speed of rotation.

2. Unbalance can be defined as the unequal distribution of weight about the centre line of a rotating part or assembly, and is redressed by submitting the assembly to a series of checks which are known as *balancing procedures*.

3. The object of balancing procedures are to *improve* the distribution of the mass of a body so that it rotates on its bearings without unbalanced centrifugal forces. This aim can only be partially achieved, for after being balanced, a body will always have a permissible amount of residual unbalance, since it is virtually impossible to eradicate it completely.

4. If it is accepted that the design and construction of the bearing housings and the casings of an engine are of the required stiffness (or strength) necessary to avoid the problem of resonance during engine operation, then the remaining bearing loads fall into the following three main categories:

- Thrust loads due to work done.
- Loads transmitted through the bearing journals due to the dead weight of the engine parts.
- Unbalanced forces due to rotation.

5. The magnitude of unbalanced forces are a square of the rotational speed, therefore the centrifugal forces produced in an unbalanced rotor during operation, can equal and sometimes exceed the rotor dead weight. When this occurs it imposes an immense strain upon the bearings, causing premature wear and the possibility of failure.

6. To produce rotating assemblies (*i.e.* compressors and turbines) that are finely balanced, all the various parts of an assembly are manufactured and machined to close tolerances. Even so, when the parts are finally assembled, because of the accumulation of the tolerances, a final balance of the rotating assembly is necessary to ensure that any unbalance is within the specified limits. The correction of unbalance may be achieved by one, or a combination of the following methods.

- Addition of weight.
- Removal of weight.
- Redistribution of weight.

7. The balancing machines that are in use in the Service today are capable of reducing unbalance to a minimum. This Chapter briefly explains the balancing procedures that are carried out on the rotating modules of modular gas turbine engines, to ensure that they satisfy the requirements laid down for pre-balanced aircraft engine modules.

STATIC AND DYNAMIC BALANCING

8. There are two methods used to locate and correct out of balance forces, these are known as;

- Static balancing.
- Dynamic balancing.

STATIC BALANCING

General.

9. Static balancing is the method used for locating and correcting unbalance in a single plane, *i.e.* unbalance that is evident centrally through the component at 90 degrees to the axis. Static balancing has a very limited application on present day aircraft propulsion systems. Its use is virtually confined to the static balancing of aircraft engine propellers. The method uses 'knife edges' to support a mandrel that passes through the hub or centre of the component being balanced, which allows the component to rotate freely. The theory being, that the point at which the wheel or propeller is the heaviest, will always gravitate and come to rest at the lowest position. For some years static balancing was used for balancing single compressor discs, and turbine rotor discs on gas turbine engines (Fig 7.5.1). However these components are now balanced on single plane balancing machines.

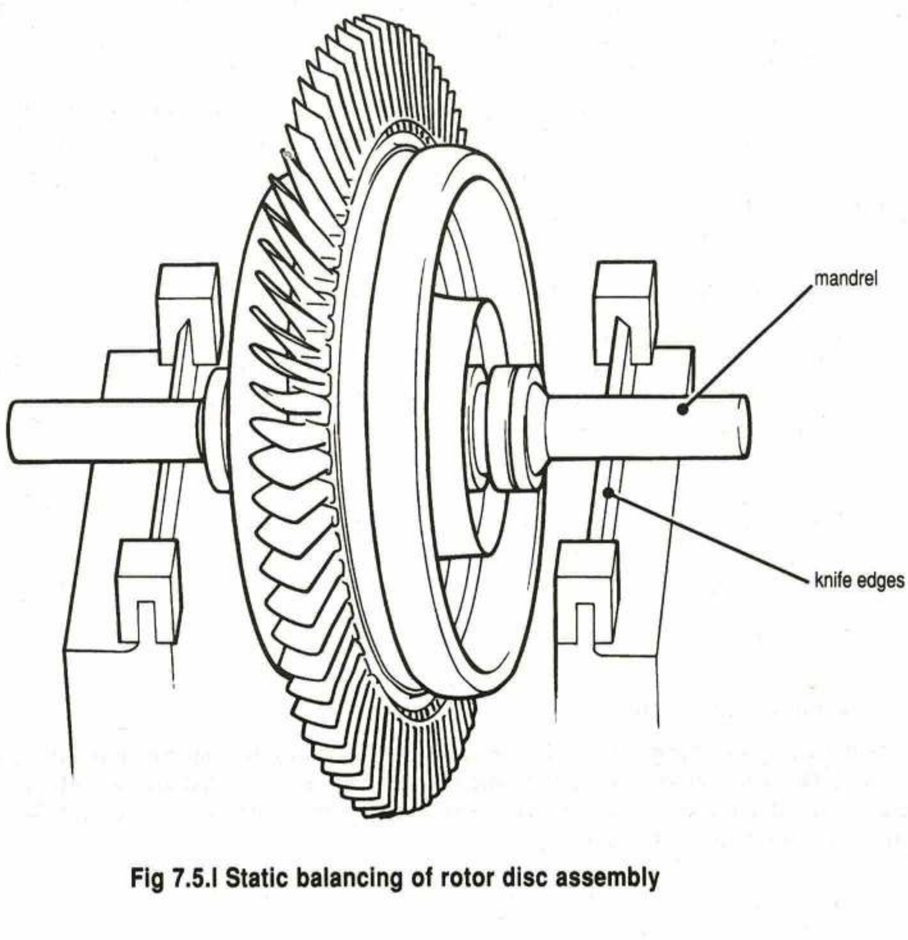


Fig 7.5.l Static balancing of rotor disc assembly

Single Plane Balancing Machines

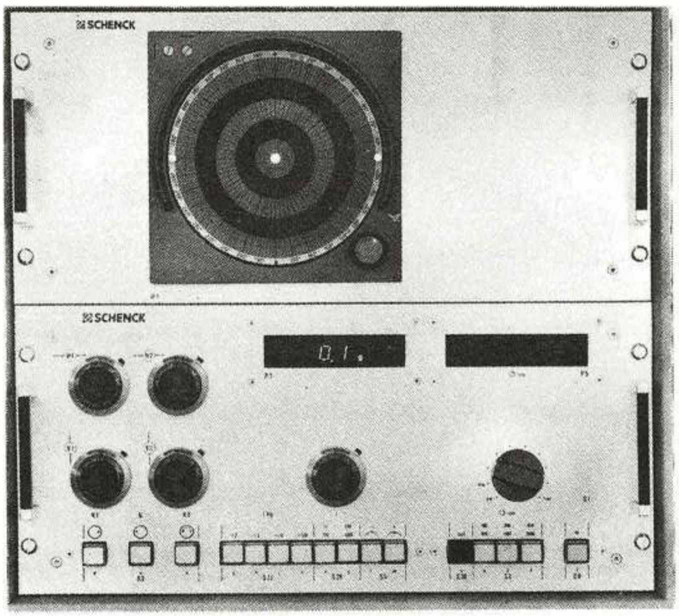
10. Single plane balancing machines (Fig 7.5.2), also known as vertical balancing machines, are used for balancing individual compressor and turbine discs, seals, and other similar rotating components. They take less time, are more accurate and are able to detect smaller unbalanced forces in a component than can be achieved by the static balancing method. However, it should be noted that vertical balancing machines are a variation of the static balancing procedure, for they balance only in the single plane. A vertical balancing machine consists of two separate main assemblies, which are:

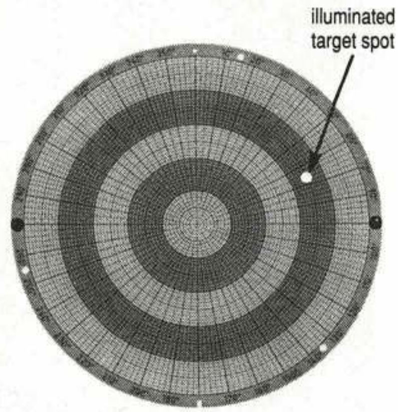
- The balancing unit, drive motor and housing.
- The electric control cabinet and the measuring unit.

Fig 7.5.2 Vertical balancing machine – single plane

11. **The balancing unit, drive motor and housing.** The vertical balancing unit has a high precision spindle that accommodates the different types of mandrel required to test the various types of rotor. The mandrels have an integral support plate onto which the rotors are clamped during the test. The drive motor housing, which is bolted to the floor, has a small square window or sight glass, which indicates to the machine operator the position, in degrees, of the rotor blade immediately above the sight window when the machine is at rest. A safety guard or shroud, that is hinged to the housing, is closed when the machine is operated.

12. **The electric control cabinet and the measuring unit.** The control cabinet, or control console, can be conveniently positioned to observe the rotor under test. It contains all the controls, switches and indicating lights that are necessary to operate the machine. It also provides a mounting support for the measuring head. The measuring head (Fig 7.5.3) includes a digital revs/min indicator of the machine speed, and a *vectormeter*. The vectormeter is a circular display indicator that is divided radially into degrees, from 0 to 360 degrees, the degrees being numbered around the outside perimeter of the indicator. It also has a concentric scale emanating from the centre, out to the circumference, that is graduated in grams (g). When the machine is in operation, and a rotor is under test, the operator is able to ascertain from the degree scale, the position of the unbalance in the rotor. From the concentric scale the operator can determine the amount of unbalance in grams, this will be the weight that is required to bring the rotor into a state of balance.





Vectormeter magnified for clarity

Fig 7.5.3 Measuring head – single plane

STATIC BALANCING OF A COMPONENT

13. **Sequence of operations**. Briefly the balancing procedure consists of the following:

- Preparing the machine.
- Preparing and mounting the rotor.
- Starting the machine and measuring the unbalance.
- Stopping the machine and correcting the unbalance in the rotor.
- Carrying out balance check runs.

14. **Preparing the machine.** Before an adaptor or an engine rotor is fitted to the machine, an initial run is necessary to prove the machines correct operation and ensure that it is registering true balance. When this is completed the adaptor or mandrel is fitted to the spindle, and the machine restarted to check the adaptor for eccentricity. Eccentricity, or unbalance, in any component being tested, including the adaptor, is displayed on the vectormeter in the measuring head. As the machine speed increases a small illuminated 'target spot' moves in an outwards direction from the centre of the vectormeter indicator, the higher the machine speed, the further the target spot travels from the centre of the indicator. When the machine revs/min has stabilized at the operating speed, the spot ceases to move. At this point the operator presses a control button which locks the target spot in that position, he then stops the machine. The distance that the target spot has travelled from the centre is a direct measurement of the amount of unbalance in the adaptor. The graduations on the concentric scale of the vectormeter from the centre to the target spot are counted. The number of divisions is the weight (in grams) required to balance the adaptor. The point at which the weight must be placed onto the adaptor, is determined by observing the division on the degree scale on which the target spot has stopped. Having noted this position, the operator then turns the machine by hand until the identical number of degrees appears in the sight glass window in the machine housing. Diametrically opposite to that position is the point where the weight must be added to bring the adaptor to a state of balance. Any unbalance in the adaptor must be corrected before the rotor is fitted. Failure to do this results in the unbalance in the adaptor becoming confused with unbalance in the rotor. If a check run indicates that the adaptor is balanced, then the rotor can be mounted and clamped to the adaptor.

15. **Balancing the rotor disc assembly.** To balance the rotor disc assembly, the procedure varies slightly to that described in para 14, however the principle remains the same. After the rotor has been clamped to the adaptor, it is usually necessary to run the machine a number of times before the rotor blades 'settle' and give a true *repeatable* indication of the rotor's state of balance. (This inconsistency of readings is known as blade scatter). When a true indication of unbalance is observed on the vectormeter, the operator adjusts the rotor weight to bring the unbalance within permissible limits. This is achieved by interchanging the rotor blades between one position and another.

16. All the blades have been weighed before they were assembled onto the rotor disc, each blade being marked with its individual weight. The operator rearranges them, interchanging heavy and light blades (being guided by the radial and concentric scales on the vectormeter), until the unbalance is within acceptable limits. This is a trial and error procedure, possibly requiring several machine runs until a satisfactory result is realized.

17. There remains one final check in the balancing procedure of the rotor disc assembly, that is the 180 degree check (also called the tooling error check), to compensate for any mounting eccentricity between the disc assembly and the rotor. The check consists of starting and running the machine to the operating speed, allowing the vectormeter target spot to settle, and taking a reading. The machine is then stopped, the rotor unclamped and then carefully rotated through 180 degrees before being reclamped to the adaptor. The machine is then run for a second time and a reading taken from the vectormeter. Both of these readings should be similar. If they differ, the reading from the second run is the actual unbalance in the rotor, and the difference between the two readings is unbalance due to eccentricity in the rotor mounting. It is compensated for by rotor blade redistribution. It may be necessary to repeat para's 16 and 17 until the results are satisfactory When this check is complete the rotor disc assembly is considered to be balanced.

18. **Balancing a rotor disc.** Should it be required to balance a rotor disc separately (without the rotor blades fitted) the balancing procedure is similar to the method used when balancing the adaptor; plus a 180 degree rotational check.

DYNAMIC BALANCING

General

19. When it is necessary to locate and correct unbalance in compressor or turbine assemblies, because of their length, unbalance may be present at various positions along their axis. Such unbalance cannot be corrected by single plane balancing. Therefore, where a number of unbalance conditions are distributed throughout the rotor assembly, corrections are made in two planes. For it is always possible to find a combination of two unbalance weights, that are the equivalent of all of the unbalance present in a rotor assembly. This is known as dynamic balancing.

20. The rotor assembly illustrated by Fig 7.5.4 shows that the total unbalance in the rotor assembly has been reduced to an equivalent system of two unbalances, A and B. The rotor is in static balance because the weights at A and B are equal and opposed to each other However, when the assembly is rotating, each weight produces its own centrifugal force which is in opposition to the other, resulting in the tendency to turn the assembly end-over-end. This action is restricted by the bearings, which results in stresses and vibration being generated in the assembly. It will be seen therefore that to bring the assembly to a state of dynamic balance, an equal amount of weight must be added to P and 0 (or removed from A and B). Thus it may be said that a part is dynamically balanced when the 'couples' set up by centrifugal forces are in equilibrium

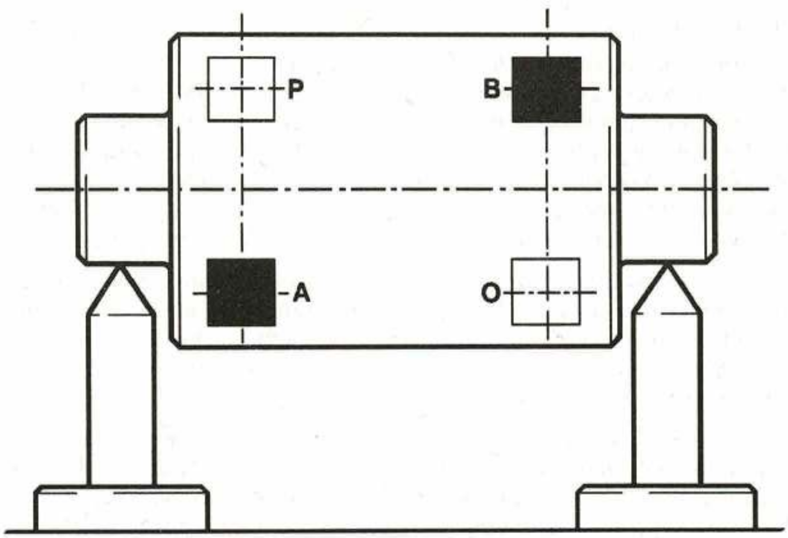


Fig 7.5.4 Unbalance couples in rotor assembly

Horizontal Balancing Machines

21. The dynamic balancing of compressor and turbine rotor assemblies are carried out on a horizontal balancing machines (Fig 7.5 5). Fundamentally the balancing principles are the same as those of the vertical balancing machines, that have been discussed previously in this Chapter. However, there are two basic differences, which are as follows:

- That the rotor under test is mounted horizontally onto the machine, and is supported at each end on a pedestal
- There are two vectormeters in the measuring head, one for each of the balancing planes.

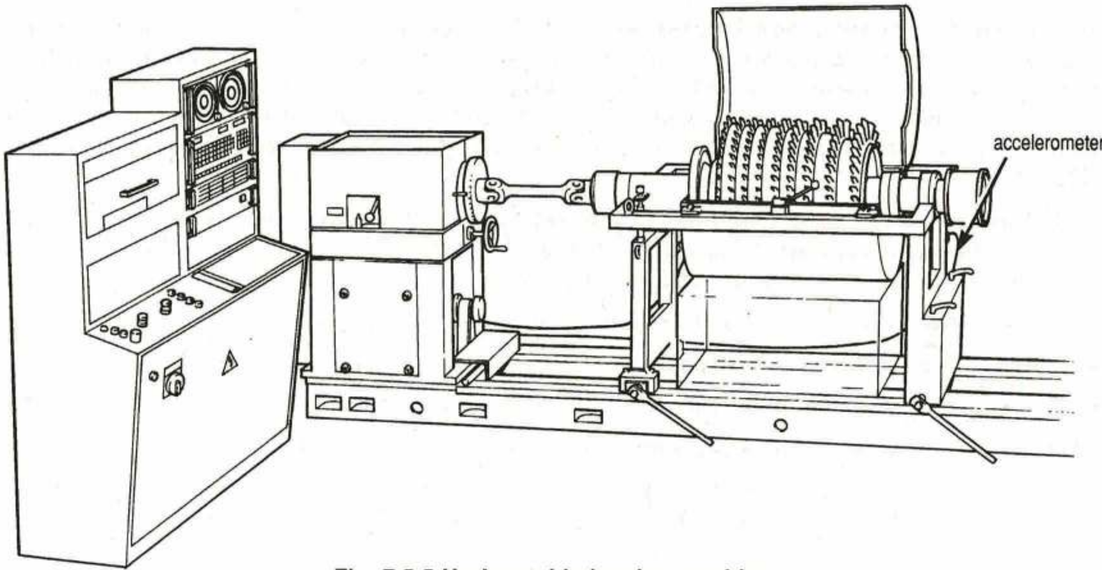


Fig. 7.5.5 Horizontal balancing machine

22. The machine consists of two separate major assemblies, which are:

- The balance unit, drive motor and housing, and pedestals.
- The electric console and measuring head.

23. **The balance unit, drive motor and housing, and pedestals.** Unlike single plane machines that operate at a fixed revs/min, the horizontal machine drive motor has a gear box (with four gears) and a variable speed range. The motor drives a shaft that has universal joints at either end for ease of alignment with the rotor. The drive shaft passes through the centre of a circular degree indicator attached to the side of the drive motor housing (Fig 7.5.6). The indicator is graduated in degrees from 0 to 360, the degrees being marked around the circumference of the indicator. The pedestals on which the rotor is mounted are adjustable to accommodate the various types and sizes of rotor. Attached to each pedestal is an accelerometer that is connected to the measuring head computer.

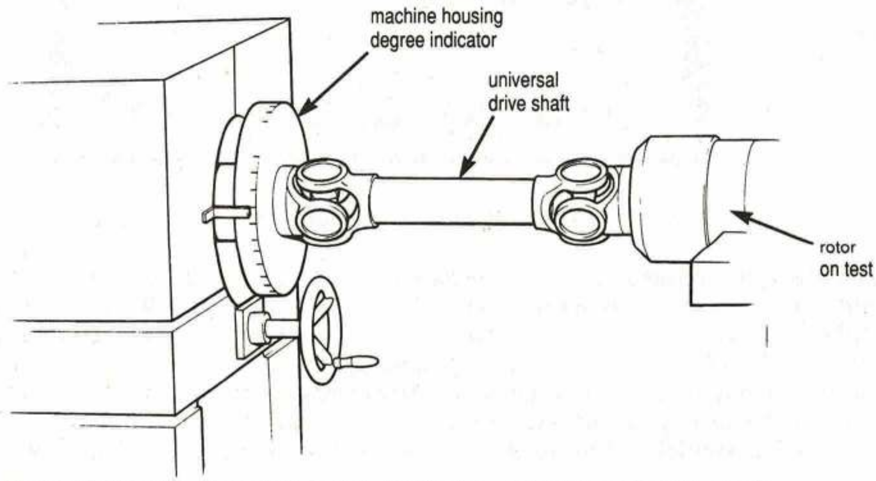


Fig 7.5.6 Machine housing degree indicator and universal drive shaft

24. **The electric console and measuring head.** The electric console, can be situated at any convenient position and houses the controls, switches and indicating lights necessary to operate the machine. The measuring head has two vectormeters and retention buttons, these retain the illuminated target indicators at any required position after the machine has stopped. It also has a digital revs/min indicator, and a number of dials for 'dialling' in data to the measuring head computer (Fig 7.5.7).

25. Before each rotor balancing run can proceed certain information must be entered into the computer, to ensure accurate balancing of the rotor assembly. The information is *dialled* into the computer by the machine operator and will include:

- The distance from each pedestal to its balancing plane.
- The distance between balancing planes.
- The radius from the centre of rotation to the balancing lands.

NOTE: (1) The centre of rotation is the centre line of the rotor shaft.

(2) A balancing land is a pitch circle on a rotor disc around which balancing weights can be added or removed.

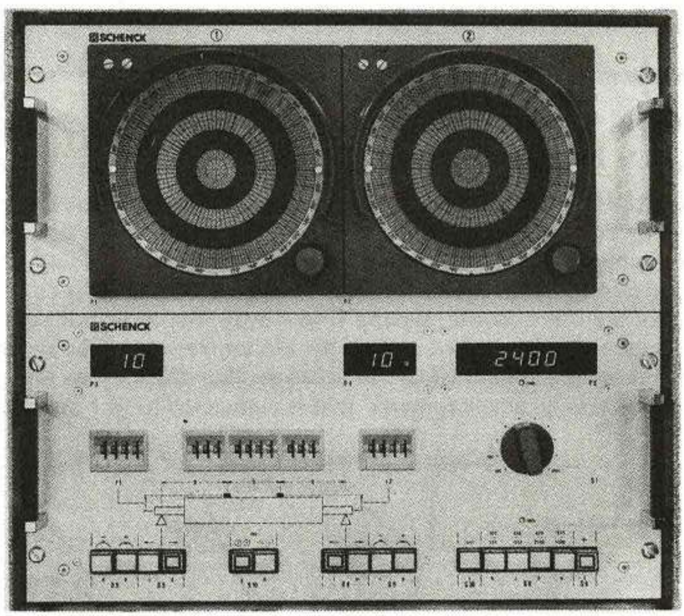


Fig 7.5.7 Measuring head – horizontal balancing machine

26. **Pre-balanced modules.** All new or reconditioned rotating modules received from Third Line or Fourth Line servicing units are pre-balanced. Pre-balancing means that a module will not require any further balancing checks or adjustments before it is fitted to a gas turbine engine and is put into service. This is made possible by the balancing procedures that are carried out at each build stage, as the rotating module is assembled, the procedure ensures the accurate balancing of the rotors own mass, and also assesses and compensates for any adverse influence that the rotor may exert upon its mating assembly when fitted to an engine. For there are occasions when manufacturing

tolerances result in a slight geometric error in the jointing face of the rotor coupling, that can cause unbalance during rotation *in the assembly to which the rotor is coupled.* To determine the degree of the unbalance generated in the mating assembly, the rotor to be tested is coupled to a dummy mating rotor (Fig 7.5.8), and the complete assembly is mounted in the horizontal balancing machine throughout the entire test run. The dummy mating rotor must reproduce the weight, centre of gravity, and dynamic characteristics of the actual rotating assembly that it is replacing. Therefore dummy rotors are accurately manufactured and frequently checked for damage and balance.

27. **Balancing the rotor assembly.** The rotor and dummy rotor are coupled together and the assembly is mounted onto the machine pedestals. A datum mark on the rotor (ø) is aligned with the "0" degree mark on the circular degree indicator on the machine housing, and the rotor is clamped in that position. The shroud or guard is placed over the rotor completely enclosing it. This is both for safety and convenience, the shroud will contain any flying debris, and also prevent violent air flow disturbances in the workshop that result from rotor blade rotation.

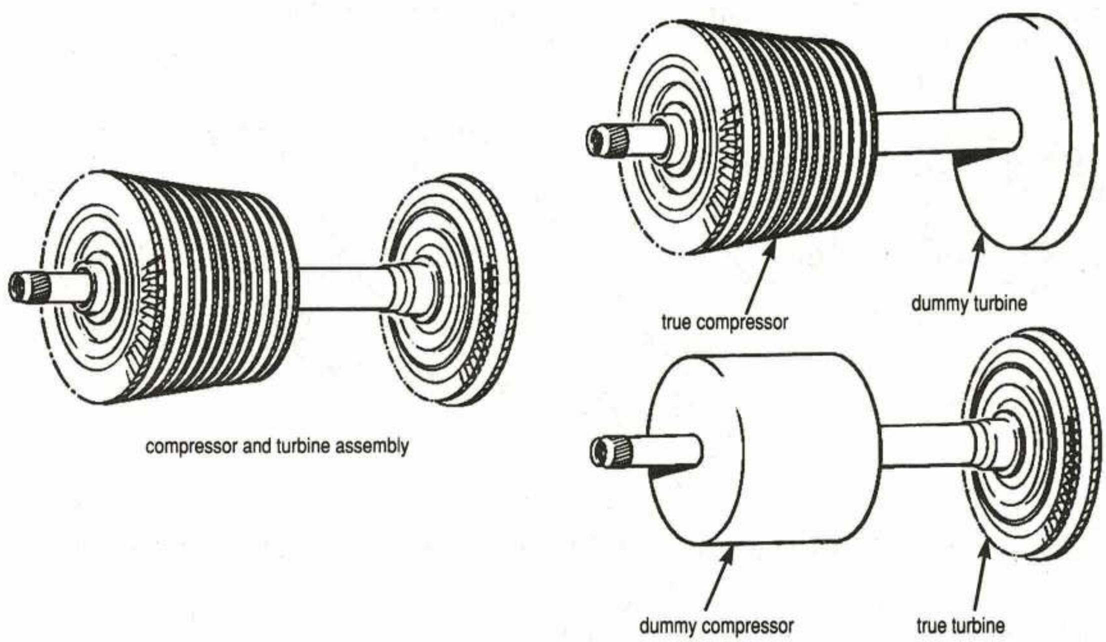


Fig 7.5.8 Simulated engine rotor assembly

28. The rotor running tests on the dynamic balancing machine do not differ greatly from those that are carried out when balancing in the single plane. The principles and methods of detecting unbalance are almost identical. The differences being that two vectormeters are required, (one for each balancing plane), and the machine speed is variable. After the test run the angular position of unbalance indicated on the vectormeters are read across to the rotor on test by realigning (by hand) the datum mark on the rotor, with the "0" on the degree indicator on the machine housing. The points on the rotor that line up with the graduations on the degree indicator, reflecting the vectormeter readings, are the positions of unbalance. When the correcting balance weights have been fitted and secured to the rotor assembly, further runs are carried out to ensure that the unbalance is now within limits, and also that the rotor assembly satisfies a 180 degree check.

29. **Correcting unbalance in the rotor assemblies.** The method for correcting the unbalance in rotor assemblies is by the addition (or removal) of weight. The type of weight that is used varies for the different rotor assemblies. For example, unbalance in compressor assemblies may be rectified by replacing the regular blade retaining pins with retaining pins that have heads of a different thickness, the heads may be reduced in thickness by grinding for fine adjustment. These retaining pins weigh one gram heavier than those that are normally fitted. A maximum of four balancing pins may be fitted to balance a compressor. The balancing weights used on turbine rotating assemblies include special weights and bolts, and balancing washers. The weights and the heads of the bolts can also be ground for fine adjustment. Each rotating module has a balancing plane with a land, around which the weights, bolts or washers may be fitted. Limits are laid down restricting the amount of weight that may be added to balance each rotor assembly. An appreciation of how weight is affected by the speed of rotation may be gained from the following example. A *one ounce* weight fitted to a compressor or turbine disc at a six inch radius from the centre of rotation, will, at 1900 revs/min, generate a force of *1.71 tons (3845 lbs*—which is roughly the equivalent to a family saloon car with four passengers). Such a force creates immense stresses on the disc, the shaft, the bearings and the bearing housing. Examples of some of the balancing weights that are used are illustrated by Fig. 7.5.9.

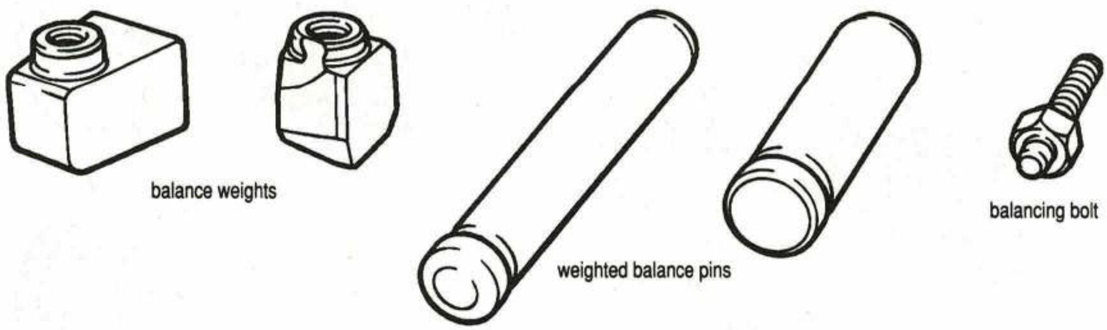


Fig 7. 5. 9 Balancing weights for compressor, turbine discs, and stub shafts

Rotor Blade Mass Moment Weighing

30. On many gas turbine engines the rotor blades represent a significant amount of the rotor mass. Additionally with the introduction of 'precision casting' fewer blade surfaces are now machined, consequently blade sets of the same type although appearing to be alike, can differ considerably in weight and centre of gravity. If a set of unweighed blades are assembled onto a disc in a random manner, there is a strong possibility that a severe state of unbalance in the rotor will result, which greatly increases the work required when the rotor is dynamically balanced. Therefore, the procedure is to weigh all rotor blades, and from the results obtained, allocate an accurate sequence of blade distribution onto the rotor disc.

31. Small blades are simply weighed on special electronic scales that are accurate to one hundredth of a gram. This is known as 'dead weighing'. Large blades are mass moment weighed.

Mass Moment Weighing

32. This procedure not only determines the mass of the blade, but in addition establishes the radial position of the blade's centre of gravity, in other words, mass moment weighing determines the blade's unbalance. It is expressed in gram millimetres (gmm). There are a number of methods used to verify the mass moment of rotor blades, the most widely used being the 'beam type' scale (Fig 7.5.10). This involves setting the blade into a holder that is attached to a beam on the scale. The blade beam assembly pivots at a fulcrum point, which is located at exactly the same distance from the blade root as the normal root working radius, when the blade is assembled onto the rotor. At the other end of the beam is a pan onto which various weights are placed to balance the blade moment. To avoid the need for fine weight adjustment, a load cell is interposed between the weight pan and the fulcrum point. This enables small weight differences to be measured electrically, thus permitting fine balancing results to be achieved. To determine the absolute moment, it is necessary to add or subtract the load cell display reading from the total weights in the pan. The blade mass and moments are then marked on the blade.

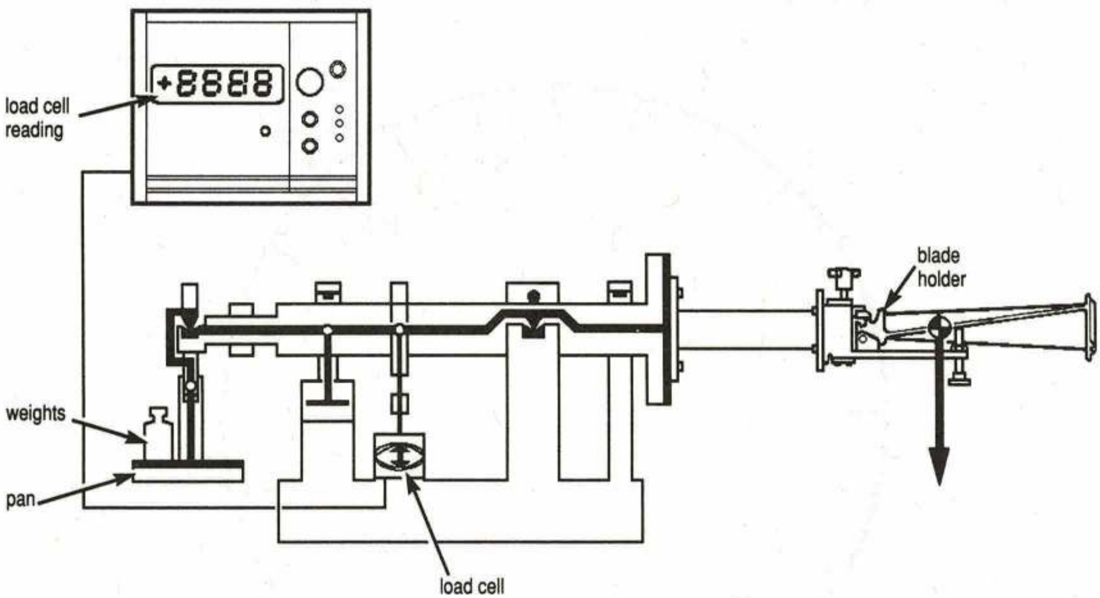


Fig 7.5.10 Beam type scales with computer

Blade Distribution.

33. Many variations of blade distribution have been devised. A brief description of two of the methods used are as follows:

- Light-heavy distribution method.
- Computerized distribution.

34. **Light-heavy distribution method.** The light-heavy method of blade distribution is as follows:

- Lay the blades out in descending order of mass.
- If there is an odd number of blades, remove one blade of average mass and place it to one side.
- Fit the lightest blade into the disc, and then fit the next lightest diagonally opposite to it (Fig 7.5.11).
- Fit the heaviest blade next to the lightest blade, and the next heaviest diagonally opposite.
- Repeat the procedure until all of the blades have been fitted.
- Finally, if an odd blade was removed at the beginning of the sequence, it can now be fitted into the last remaining slot.

35. This method of distribution considerably reduces the amount of time and work required when the rotor disc assembly is balanced on the machine. However, as a rule the unbalance of the disc assembly is outside the prescribed limits and final balance is achieved by repositioning the rotor blades around the disc according to their individual moments. The unbalance being indicated on the balancing machine vectormeters.

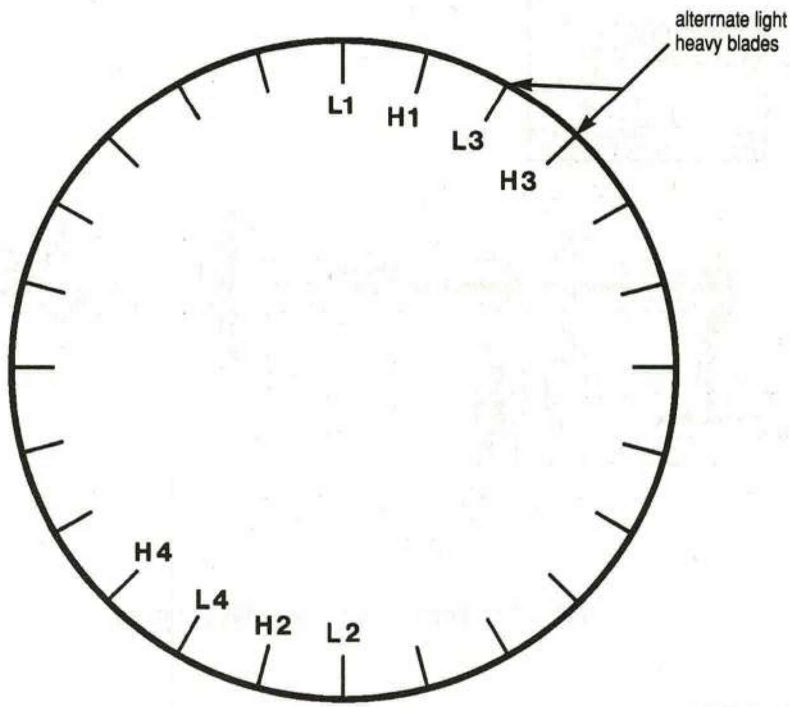


Fig 7.5.11 Light heavy distribution method

36. **Computerized blade distribution.** The use of a computer makes it possible to reduce to a minimum the work required for final balancing of the rotor disc assemblies. This is the latest method of rotor blade distribution in which a computer is operated in line with the moment scales. Data of the measured blade moments is automatically passed to the computer from the load cell of the moment scales. From this information, the computer calculates and prints an optimized distribution

plan, from which the blades are assembled onto the disc. Only minor final machine balancing is required of the disc/blade assembly, when this method of blade distribution is applied.

37. If, as in some cases, the unbalance of the compressor or turbine disc is first measured, and the amount of unbalance and its angular position on the disc (in relation to a datum mark) is entered into the computer along with the blade mass moment data. The computer can be programmed to calculate the blade distribution plan in such a manner that the disc unbalance is compensated for as the blades are assembled, *obviating the necessity to dynamically balance the disc/blade assembly.*

Rotor Build-up Balancing Checks

38. Balancing checks are generally carried out on the following components at the appropriate stages during the build up of a module assembly.

- Compressor and turbine discs.
- Compressor and turbine rotor blades.
- Compressor and turbine disc and blade assemblies.
- Compressor and turbine assemblies (with shaft, disc assemblies, rotating seals and spacers) and dummy rotors.

39. The rotor discs that carry *large* compressor or turbine blades are not balanced independently, but are balanced as a blade disc assembly. The unbalance in the disc can be rectified by interchanging the blades from one position to another. The weight differences between large blades is sufficient to compensate for unbalance in the disc.