The Part Thermo-Mechanical Analysis Plays in the Design of Gas Turbines

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ABSTRACT

Many components within modern gas turbines are designed to operate at conditions close to the material limits to allow it to be adequately optimised for life cycle cost, weight and life etc. To do this it is necessary to have a better understanding, and predictive capability, of the behaviour of these components, which may include thermal behaviour. Presented here is an overview of the thermal analysis process currently being applied to civil aero engines designed at Rolls Royce, many aspects of these processes are also applied to gas turbine components used in other parts of the business. The document describes the individual parts of the process and explains how the data is used to support the design verification process.

1.0 INTRODUCTION

Two of the main drivers in the design of new civil gas turbine aero engines are; low environmental impact and competitive products. Low environmental impact means a low SFC (Specific Fuel Consumption) giving low CO_2 emissions, low combustor generated emissions HC, CO and NOx etc, low noise and low manufacturing footprint. Competitive product means low cost of ownership (typically initial cost, fuel, maintenance and resale value). The solutions typically requires a high overall pressure ratio, high turbo-machinery efficiency and the minimum use of cooling air. This then places the following constraint on the design of many of the components within the engine:

1) Low cost (both material and manufacture).
2) Capable of operating at high temperatures.
3) Long and reliable service lives.

These requirements may contradict and therefore to fully optimise and underwrite a design it is necessary to understand the thermo-mechanical behaviour to a relatively high level of confidence.

In addition to the above, to certify the engine it may be necessary to demonstrate by analysis that certain components have an adequate integrity and can cope with certain failure conditions, typically understanding the thermal behaviour of these components to an adequate level of confidence is essential.

2.0 ANALYSIS TYPES

Although it is possible to solve some heat transfer problems by hand calculations and spreadsheets etc. the complexity of modern gas turbines general precludes this. Conjugate heat transfer is sometimes considered but it is generally too slow and inflexible for general use. Typically the analysis will use Finite Element models where the solids are represented by either ‘2d’ or ‘3d’ meshes and have boundary conditions applied to them. The remainder of this review will concentrate on the Finite Element modelling approach to component temperature prediction.

Within Finite Element modelling there are two key groups of analysis; two dimensional (usually axisymmetric about the engine centre-line) and three dimensional, however, many of the principles involved are similar.

2.1 Geometry

The geometry used in FE models is typically generated using a proprietary CADDS (Computer Aided Design and Draughting) package, typically in IGES file form for '2d', see Figure 3-1, and 'step' or 'parasolid' form file for '3d' geometry, see Figure 3-2. The argument for '2d' vs. '3d' will depend on both how well the component can be represented '2d', the modelling fidelity required and the time available for the analysis.

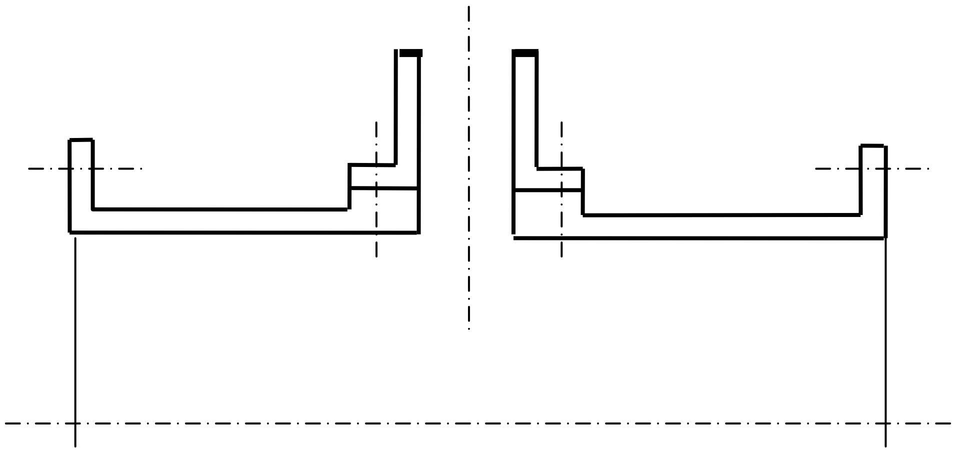

Figure 3-1: '2d' Casing Geometrical Representation.

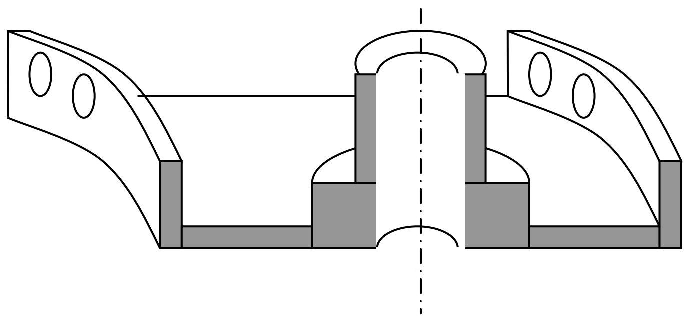

Figure 3-2: '3d' Sector Geometric Representation.

The extent of the component or assembly that will need to be included in the model will generally be down to experience and can come down to a balance between accuracy and computational time. Figures 3-1 and 3-2, above, show a representation of a casing with a 'boss'. If the object of the exercise is to determine the casing thickness etc. then a '2d' analysis may suffice, however, if details such as, the effects boss fillet radii have on component life, are to be assessed then it is likely a '3d' analysis would be required.

It is often both desirable and necessary to perform a certain amount of 'de-featuring' of the geometry to take out certain features such as small fillets and holes etc.

Figure 3-3 shows an example of 'actual' and 'de-featured' geometry, the general rule is de-featuring should always result in 'metal-on' and not 'metal-off', preventing any *'mapping ambiguity'* problems when transferring temperature data to stress models.

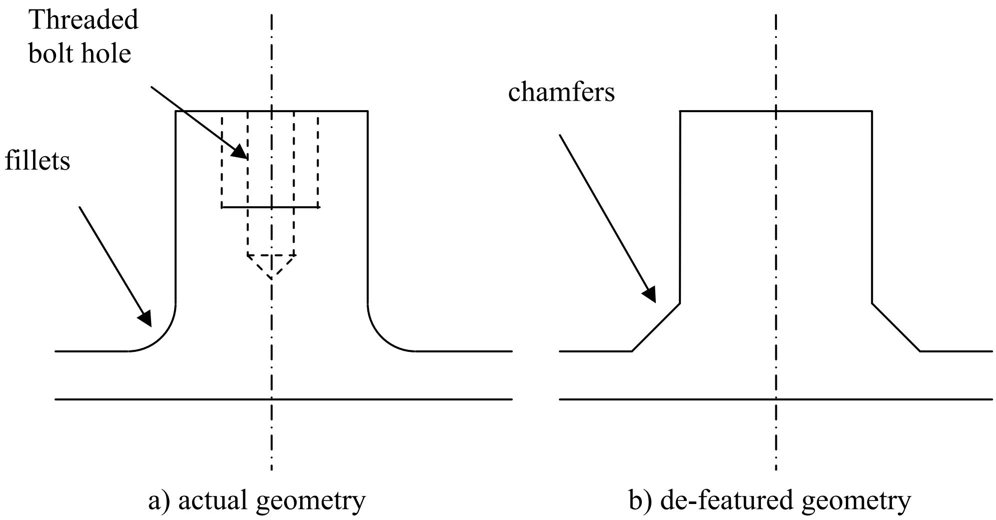

Figure 3-3: a) actual geometry and b) de-featured geometry.

2.2 Mesh

In general it is usually possible to achieve the necessary temperature and displacement accuracy with most element types. If the ultimate purpose of the model is to produce a thermo-mechanical model capable of predicting stresses then consideration needs to be made on the effects of the element type and density on stress accuracy.

For '2d' analysis SC03 (the main RR FE thermal program) uses an adaptive 6 node element triangular mesh which automatically generated within the program. Although these may be computationally more expensive than a block mesh, for the equivalent accuracy, this is seldom a problem with '2d' analysis as the advantages of auto meshing outweigh the computational time. Figure 3-4, below, shows an example of a '2d' triangular mesh. Note: equilateral triangles are better for accuracy; however, less accurate shapes are required to fit the geometry, because the calculations may contain small pivotal denominators'.

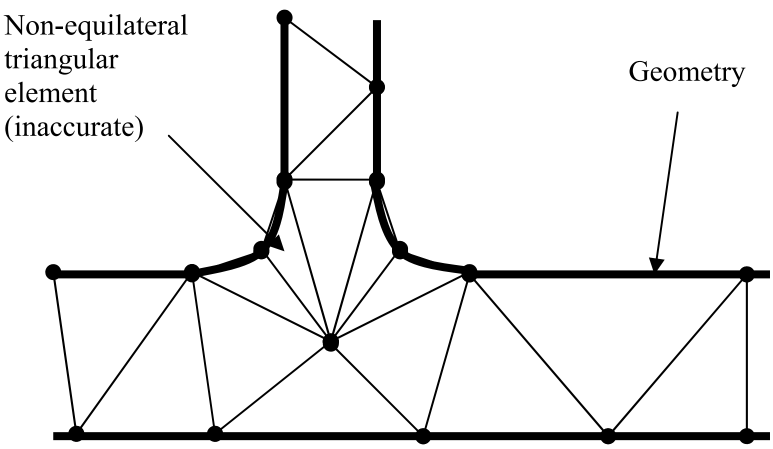

Figure 3-4: '2d' Triangular Meshed Geometry.

For ‘3d’ analysis the situation is currently different. SC03 has a ‘3d’ auto meshing facility that produces a 10 node tetrahedral element mesh, a typical example is shown in Figure 3-5. This will require a large number of elements, and hence nodes to achieve the required accuracy, which can result in a computationally expensive analysis. It is also possible to import a mesh; that has been produced by another program, into SC03. These could be better tetrahedral meshes or alternatively ‘brick’ meshes, as shown in Figure 3-6 below. It is the responsibility of the analyst to pick the appropriate mesh for the job balancing the time taken to construct the mesh, the time taken to run the analysis and the accuracy.

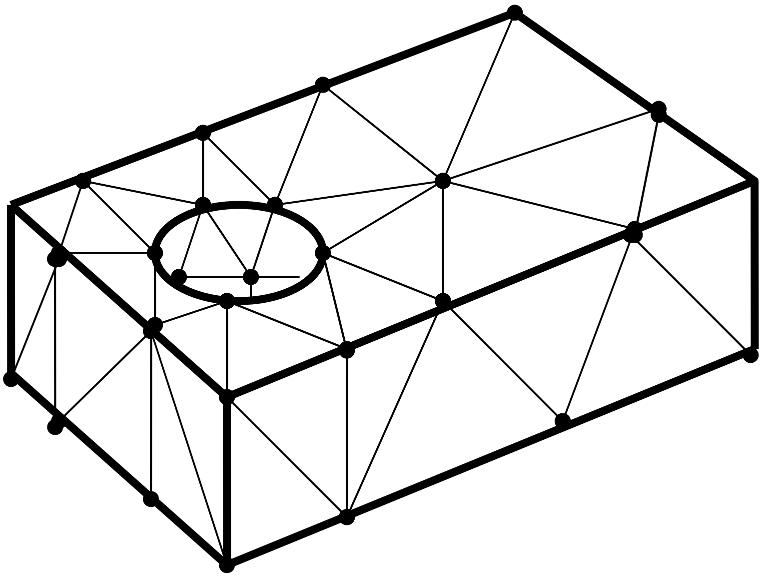

Figure 3-5: ‘3d’ Tetrahedral Meshed Geometry.

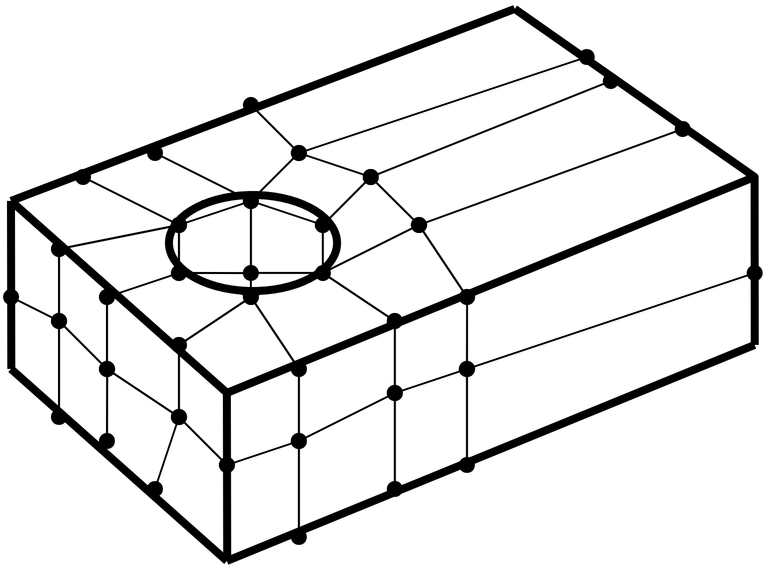

Figure 3-6: ‘3d’ Brick Meshed Geometry.

If there is any doubt regarding the effects of mesh density on accuracy, an answer is to keep refining the mesh until a ‘mesh independent’ solution is achieved. Note: most equivalent commercial codes have similar meshing capabilities either directly within them or through associated CADDS packages.

2.3 Joints

If the model is to be created to run a thermo-mechanically it will be necessary to specify systems of joints that allow the appropriate relative mechanical movements. Even if the model is thermal only it may still be necessary to specify systems of joints to break the full conduction path between adjacent components and then, if necessary, re-establish a partial conduction path to simulate the effects of TCC (Thermal Contact Conductance). It has been demonstrated that, in certain situations, it is necessary to determine the magnitude of the TCC to achieve an accurate prediction of temperatures.

A considerable amount of research has gone into trying to develop a reliable method of predicting levels of TCC as a function of the relevant input parameters. However, much of the research has been aimed at areas such as cryogenics and electronics which are of little direct relevance to gas turbine design verification. As a result of this Rolls Royce have instigated a programme of work aimed at developing a suitable correlation that will be valid for materials and operating conditions found in modern gas turbine engines.

Figure 3-7 shows a magnified schematic surface showing the contact points and the constriction of heat flow which generates the resistance. A schematic of the temperature profile across the joint is shown in Figure 3-8. Figure 3-9 shows a plot of TCC vs. pressure for two surface finishes.

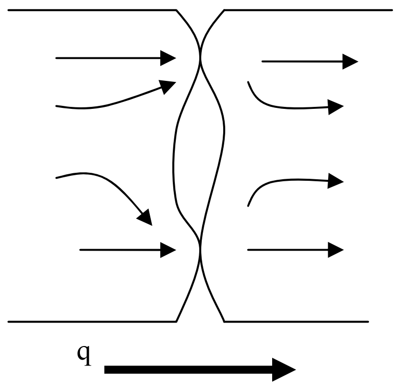

Figure 3-7: Magnified Surface.

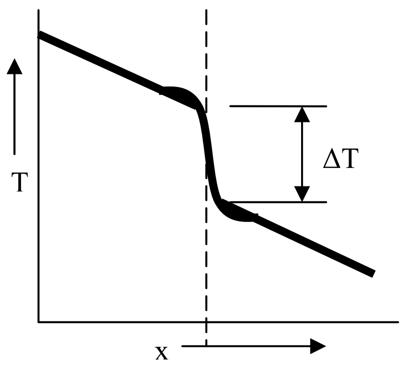

Figure 3-8: Temperature profile.

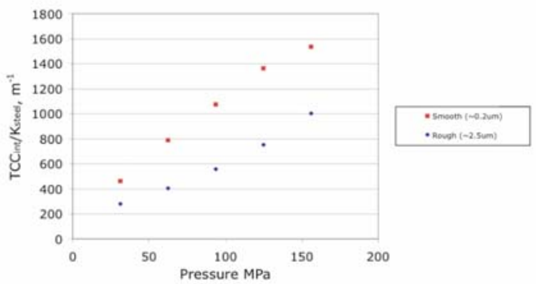

Figure 3-9: TCC vs. pressure.

2.4 Engine Performance

The boundary condition may be either convective and/or radiative which are typically either directly or indirectly related to the main annulus performance parameters. Figure 3-10, below, shows a schematic of a gas turbine, the performance stations and the variation of pressure, temperature and mass flow rate through the engine. A performance model will then provide dimensional pressures, temperatures and mass flow rates for each station i.e. P1.0, T1.0 and W1.0 respectively.

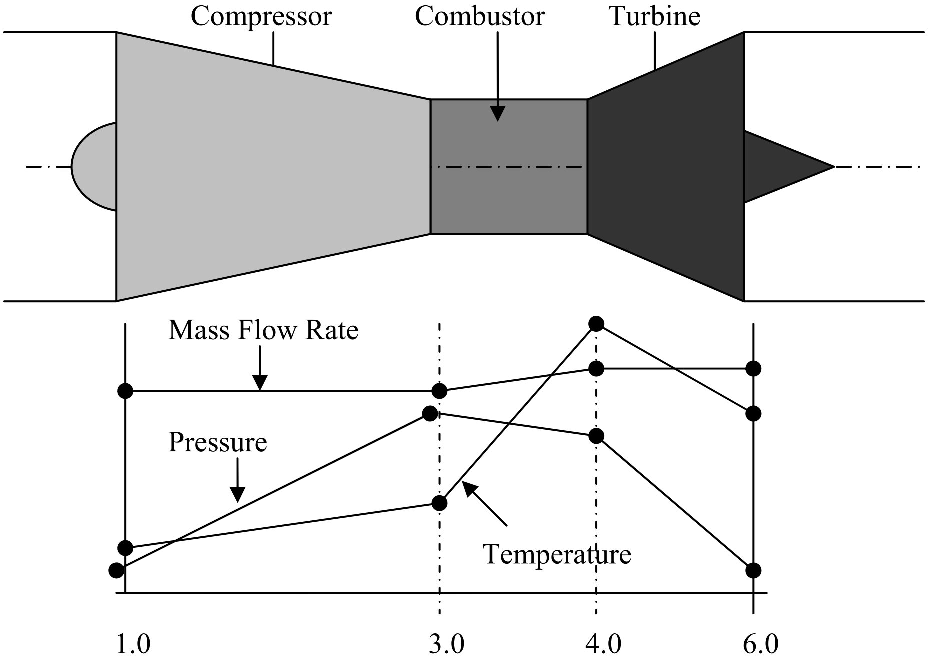

Figure 3-10: Schematic of Gas Turbine Showing Performance Stations and Variations.

It is then possible to produce this performance data for various engine and environmental conditions to provide pseudo transient performance for a given sequence of engine conditions/manoeuvres, such as fast ‘accels’ and ‘decels’ etc. An example of T3.0 (compressor delivery temperature) against time for a ‘square’ cycle is shown in Figure 3-11 below:

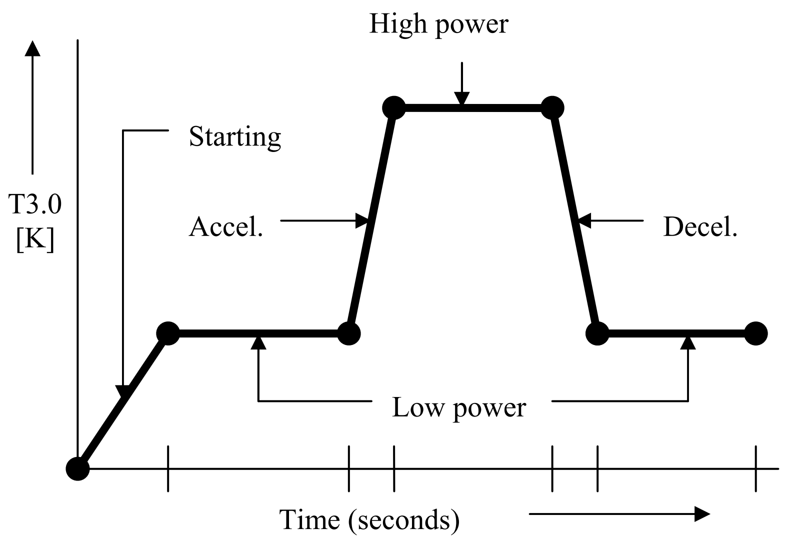

Figure 3-11: Variation of T3.0 with time for a 'square' cycle.

If the analysis requires a more detailed transient performance definition it is possible to use either a 'multi-point' or true transient performance.

2.5 Secondary Air System

Most gas turbine engines have a secondary air system to; seal disc rims, seal bearing chambers, control bearing loads and purge cavities. This air can form part of the component thermal boundary conditions as shown in Figure 3-12 below:

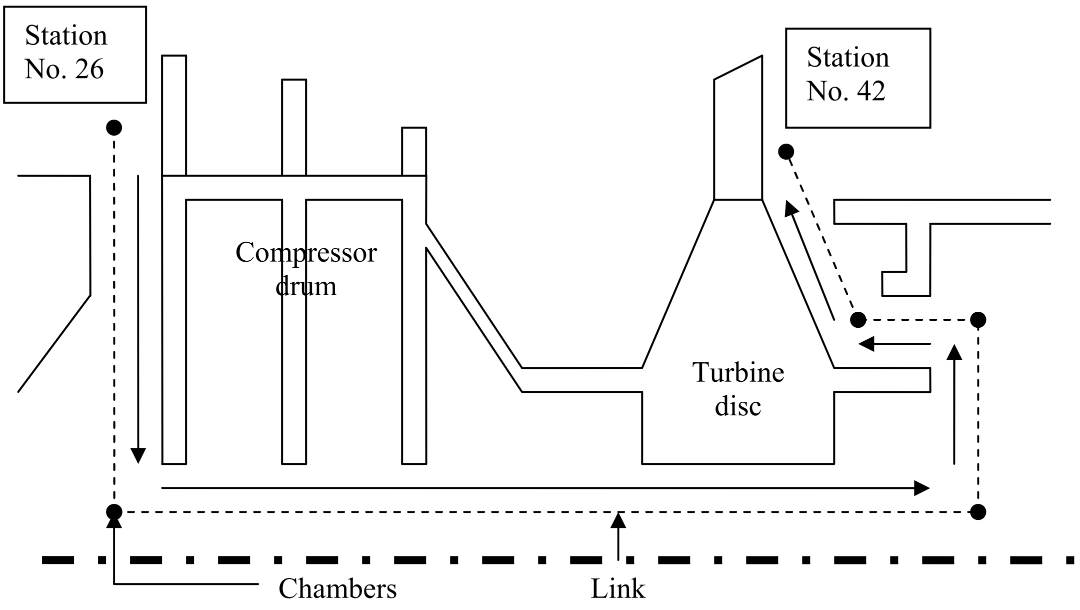

Figure 3-12: Schematic of Gas Turbine Showing Secondary Air System.

The behaviour of the secondary air system is normally assessed using a network solving program to determine the pressures and temperatures at the *'Chambers'* and the flow along the *'Links'* as shown in Figure 3-12 above. The parameter values are normally expressed non-dimensionally as a function of the relevant main annulus parameters i.e.

$$WL1 = 0.1 * W26.$$

2.6 Convective Heat Transfer Coefficients

For certain relatively simple configurations and flow regimes it is possible to determine the magnitude of Heat Transfer Coefficient using an analytical approach, however, for most real situations this is not viable. Therefore the magnitude of convective heat transfer coefficients is typically determined from one of the two following methods:

1) Empirical correlations – These are typically of the form:

$$Nu = A * Re^B * Pr^C \text{ (Forced convection).}$$

$$Nu = D * Gr^E * Pr^F \text{ (Natural convection).}$$

Where;

Nu = Nusselt Number

Re = Reynolds Number

Pr = Prandtl Number

Gr = Grashof Number

A, B, C, D, E and F are constants.

These are derived experimentally and it is important to ensure they represent the correct flow and geometric conditions and are being used within their range of applicability. There is a vast array of public domain and proprietary data covering, if appropriate both flow regimes (laminar and turbulent). Typical configurations covered include:

a) Forced flow in a duct, including entry length effects
b) Flat plate.
c) Free disc.
d) Pedestal arrays (staggered and in-line).
e) Natural convection.

2) CFD analysis – considerable care is needed in setting up and running the CFD models to ensure reliable predictions of heat transfer coefficients. Unless the CFD analysis is to be performed at many conditions the predictions of HTC will require scaling.

2.7 Convective Thermal Boundary Conditions

We tend to use three basic types of convective thermal boundary conditions within RR:

1) Infinite heat capacity (Convecting Zone)
2) Finite heat capacity (Streams and Ducts)
3) Zero heat capacity (Void)

Figure 3-13, below, shows the different types of basic convective boundary condition types as applied to a schematic disc model.

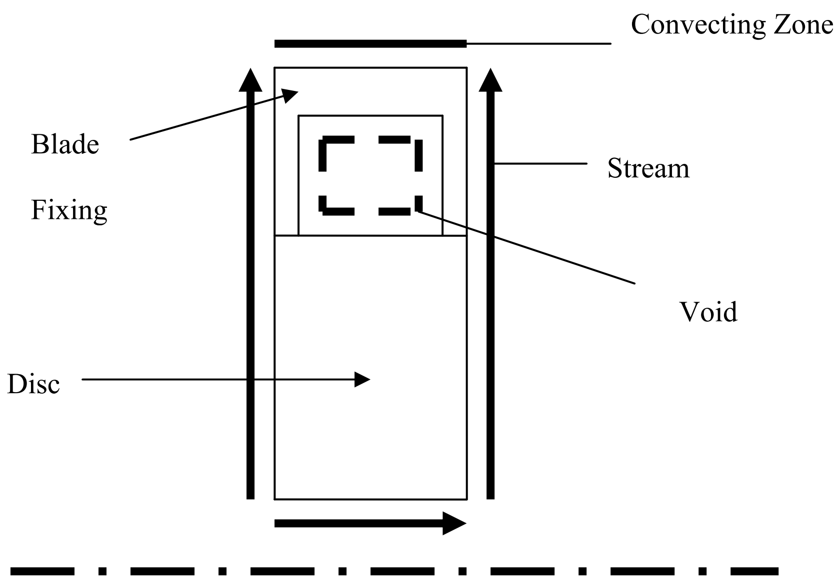

Figure 3-13: Schematic disc showing boundary condition types.

3.0 MODEL CHECKING

In the case of most models we need to simplify the physics to be able to run the model in an acceptable time frame. Also large model may easily contain hundreds of boundary conditions each with five or six lines of input containing up to 20 characters. The possibility of making an error whilst constructing the model must be considered a real one. It is arguably not possible to claim that any model is error free, however, we need to ensure that *'the model contains no errors that would have a significant adverse effect on the data it produces'*.

Techniques that are use for model checking include:

1) Check 'domain properties' material types etc.
2) Check mass flow continuity.
3) Check pressures.
4) Check Heat Transfer Coefficients.
5) Check the transient behaviour of key features by comparing the model with 'time constant' data i.e.

$$T = T_{in} + \Delta T\,(1 - e^{-t/\tau})$$

Where:

T	=	temperature as a function of time.
T_{in}	=	initial temperature (at t = 0)
ΔT	=	temperature change

t	=	time
τ	=	time constant = V ρ SpHt. / (h A)
V	=	volume
ρ	=	density
SpHt	=	specific heat capacity.
h	=	heat transfer coefficient.
A	=	surface area.

If the model is to be used to predict displacements it will be necessary to check both the direction and magnitude of the deflections. The thermal movements can be predicted by either $\delta = R\,\alpha\,\Delta T$ or $\delta = L\,\alpha\,\Delta T$ and the mechanical movements from the appropriate expression.

4.0 MODEL VALIDATION

By ‘Model Validation’ we mean comparing predicted parameter (temperature) data with measured data from the same engine and run over the same sequence of operating conditions to ensure there is an acceptable agreement (i.e. *‘fit for purpose’* e.g. 5°C steady state and 15°C transiently). The type of validation that the model will be required to be subjected to will depend on both what the model is going to be used for and the type of data available for the component in question.

There are three commonly used types of validation of temperature data:

1) **Thermocouple** – these can give both steady state and transient gas and metal temperature data for specific locations within the engine and achieve a reasonable accuracy. Rotating components will require the use of a ‘slip ring’ or ‘telemetry system’ which may require cooling and hence may result in an ‘intrusive’ measurement technique. Figure 3-14, below, shows a cross section of the relevant part of the engine and the thermocouple positions whilst the measured, predicted and difference is plotted against time for a square cycle in Figure 3-15 at the bottom.

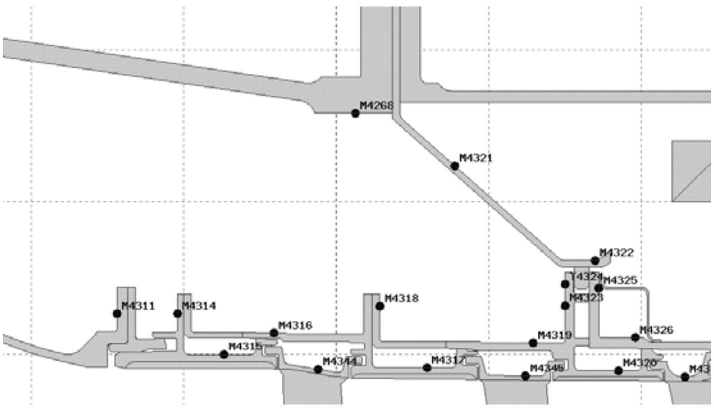

Figure 3-14: Compressor Casing showing Thermocouple Positions.

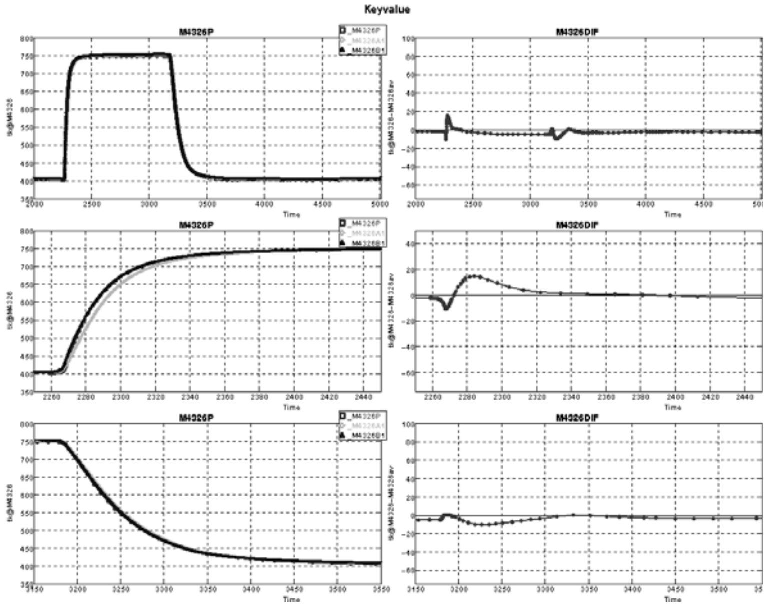

Figure 3-15: Measured, Predicted and Temperature Difference against Time.

2) **Thermal paint** – this can provide steady temperature data for an entire surface. The accuracy (+/- 4% at the change point for T > 700K) is not as good as for thermocouple data. It is best suited to relatively thin fast responding components where the time at a stabilized condition can accurately be determined. When used on top of ceramic coatings thermal paint can modify the radiation absorption characteristic of the coating and hence become an 'intrusive' technique. Figure 3-16, below, shows a view of a combustor thermal paint map, this would be compared with model predictions for the same condition. Note: temperature data is only used for the 'change points'.

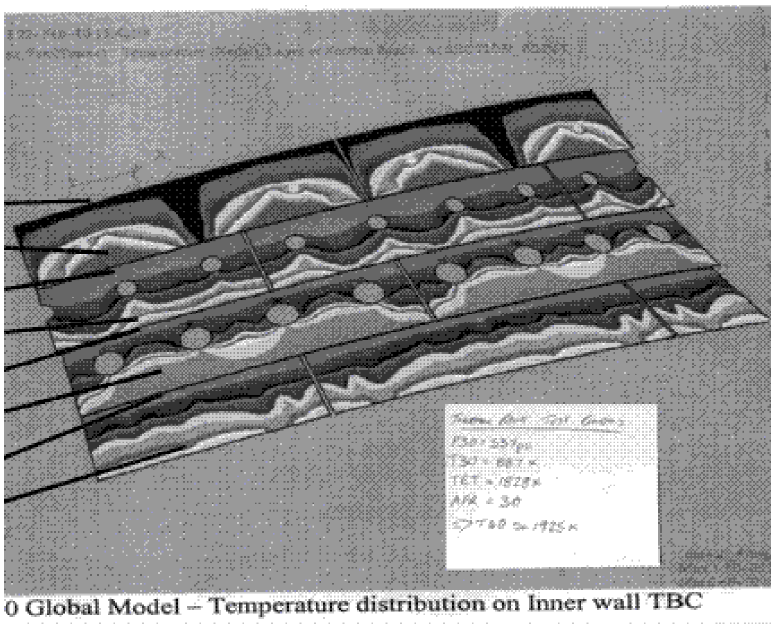

Figure 3-16: Combustor Wall Thermal Paint Map.

3) **Thermal imaging** – this technique can potentially provide transient data for an entire surface, however, it can only be used in relatively cool situation and its accuracy is not as good as the two other techniques. In some situations it is necessary to use this in conjunction with paints of a known emissivity which again can make this an intrusive technique.

The intrusive aspect of these measurement techniques is dealt with by modelling the engine components and systems together with the effect of the measurement technique. Once the model is validated the effects of the measurement technique are then removed from the model prior to using it for producing component data.

The most common form of model validation is carried out using thermocouple data as this can validate the model both steady state and transiently to an acceptable accuracy.

5.0 THERMO-MECHANICAL MODELLING

In general it is relatively straightforward to convert a thermal only SC03 model to thermo-mechanical to permit it to predict displacements, and stresses if required. Typically it is necessary to add the loads, joints and restraints and then switch the model from ***'thermal only'*** to ***'thermo-mechanical'***.

6.0 OPTIMISATION

There is increasingly more interest in obtaining a design solution that not only meets the specification requirements (life etc.) but is also optimised for cost and weight etc. This can be done by the use of an optimisation package such as ***iSIGHT***. To carry out the optimisation process it is necessary to set up a thermal analysis as part of a multifunctional assessment loop that is capable of determining life, cost and weight etc.

Figure 3-17, below, shows a schematic view of a compressor disc as an example of a component to be optimised.

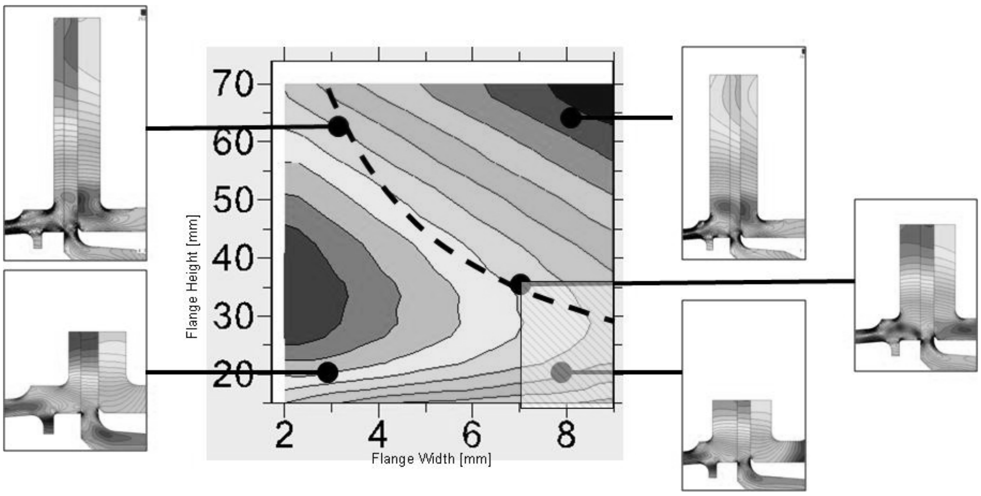

Figure 3-17: Schematic Casing Flange Assembly showing 'Design Space'.

To optimise for parameters such as weight, cost and life it will be necessary to set up the relevant models and link them using ***iSIGHT*** or an equivalent. It is important when setting up the thermal model to ensure that the thermal boundary conditions will be appropriate for geometry lying anywhere in the design space.

For example, if the heat transfer on the bore of the disc is a function of the flow area then the boundary condition must reflect it so that it is valid for all of the configuration that will be analysed

7.0 ROBUSTNESS

Gas turbine components are manufactured to vary within specified tolerance bands and hence each product will be subtly different. Traditionally in the past we have generally assessed a ‘nominal’ product, or in a few situations a ‘min tolerance’ case. However, today we are more likely to look at the statistical variation of the specification parameters to determine what proportion of the population would be compliant. Figure 3-18 below shows the PDF (Probability Distribution Function) for a design criteria parameter (e.g. component life):

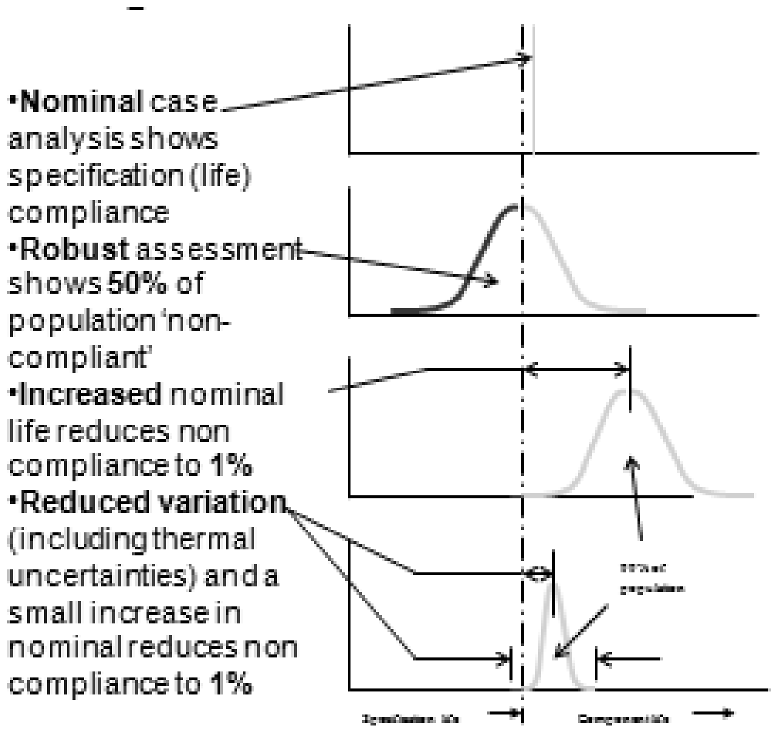

Figure 3-18: Component life Probability Distribution Function.

The aim here would be to identify all the parameters that may contribute to the variation which would typically include things such as;

1) Geometric tolerances.
2) Main annulus performance.
3) Secondary air system performance.

Note: variations in heat transfer are not considered as they tend to be as a consequence of other variable as listed above, however, thermal boundary condition uncertainty can be used as an alternative strategy. The object is then to determine which variables significantly influence the parameter of interest and then to produce a ‘response surface’ for them. This response surface is then assessed sufficient times to have a statistically valid distribution as shown in Figure 3-18 above.

An advantage of this approach is that, for example, if the life target is found to be difficult to achieve because of the width of the distribution then it can be used to determined which parameters are causing this and this may suggest a route to fixing the problem.

8.0 SHUT-DOWN BEHAVIOUR

As a result of a ‘normal’ engine shut-down many of the components within it will experience temperature asymmetry and in some cases temperatures above normal operating levels and then take many hours to cool to ambient. Current engine operation will typically require the engine be capable of restarting prior to the shut-down engine reaching stabilized ambient conditions. This may then have an effect on component lives, either advantageous or detrimental, or, in the case of thermal asymmetry, cause rotor bow, out of balance and vibration on start up.

So far in this document all the behaviour considered has been with the engine running. With the engine shut-down the heat transfer mechanisms changes and cooling is controlled by a balance of the following:

8.1 Heat Loss from the System

If the engine is in a quiescent environment with the rotors stationary then heat loss would be by natural convection and radiation. However, if the engine is outside it is likely that the cooling will be enhanced by any wind so therefore wind strength and direction may become important. It is possible that the wind speed may be sufficient to cause one or more of the spools to rotate causing air to be drawn through the secondary air system further enhancing any cooling. The point to remember here is that the cooling rate will not be unique and that a suitable range should be considered.

8.2 Heat Distribution within the System

Heat redistribution by conduction within the components will attempt to drive all the components to a single temperature. However, buoyancy driven convective flows within the cavities between the components will tend to cause the top of the engine to become hotter than the bottom.

To date this has been approached empirically with very little attempt to perform any actual modelling. Figure 3-19 shows the type of behaviour you might expect to see from a temperature survey.

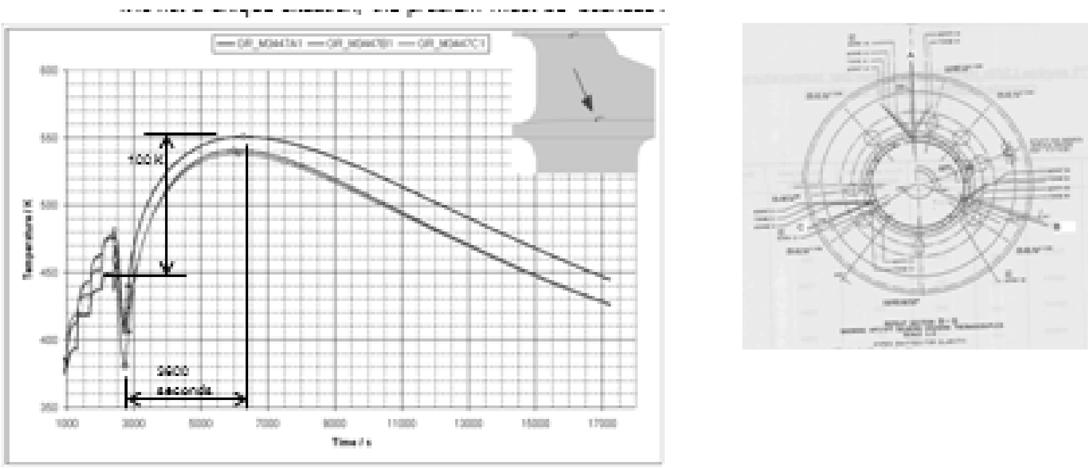

Figure 3-19: Typical Shut-down Behaviour.

9.0 THERMO-MECHANICAL DATA APPLICATIONS

9.1 Prelim Design Support (Material Selection)

To determine the most cost effective material for a component it would typically be necessary to understand its maximum working temperature.

9.2 Detailed Design Support (Stress/life Assessment)

Many components within the engine are subject to life limiting mechanisms that are temperature dependant and appropriate temperature data will be required to adequately assess their lives. A significant number of components, such as discs, are life limited by LCF (Low Cycle Fatigue) which will require transient temperatures for an agreed complete flight or mission profile. It is also important for these components to consider other potential life limiting mechanisms such as creep and oxidation etc. to ensure these do not result in a lower life. If it is judged necessary to assess this it may be more appropriate to provide the data as a time temperature exposure graph for a given mission.

Certain strain based lifing techniques may require temperature data for both the engine running and shut-down phases of typical flight cycles.

9.3 Certification Requirements

For certain classifications of components it is necessary to predict the component lives as part of the certification requirements. In addition it is necessary to demonstrate by analysis that the effects of certain failures of the control system, seals and bleed valves etc. can be adequatly dealt with.

9.4 Compressor/turbine Tip/seal Clearances

Both the efficiency and operability of the compressors, turbines and secondary air system are dependent on maintaining blade tip and seal clearances within certain limits. A significant part of the running clearances is required to accommodate the axisymmetric thermo-mechanical movements of the rotating and static parts of the seal.

A typical tip clearance configuration is shown in Figure 3-20, below, and its behaviour over a square cycle is show in Figure 3-21. This type of analysis can be used to ‘tune’ the response of the casing to achieve a tighter running seal clearance (both steady state and transiently) to achieve a more stable and efficient compressor.

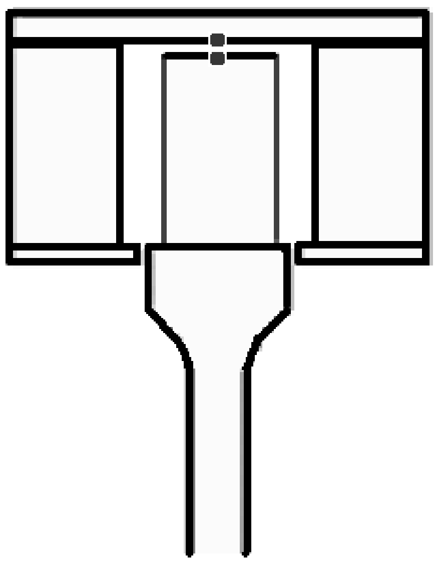

Figure 3-20: Schematic Tip Clearance Arrangement.

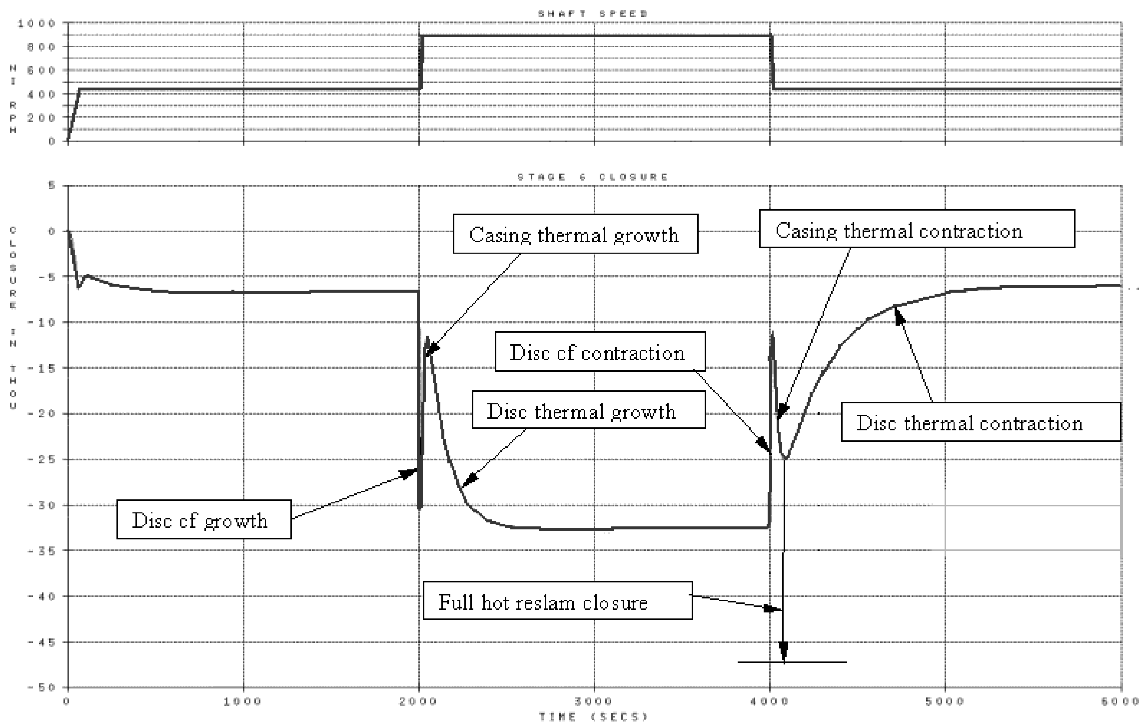

Figure 3-21: Typical Tip Clearance Over a Square Cycle.

9.5 Annulus Alignment

For optimum turbo-machinary efficiency it is typically necessary to achieve a particular 'hot' annulus line at a specific running condition (usually cruise for a civil aero engine). Thermo-mechanical analysis is therefore required to predict the 'cold-to-hot' movements such that the equivalent 'cold' annulus line can be specified.

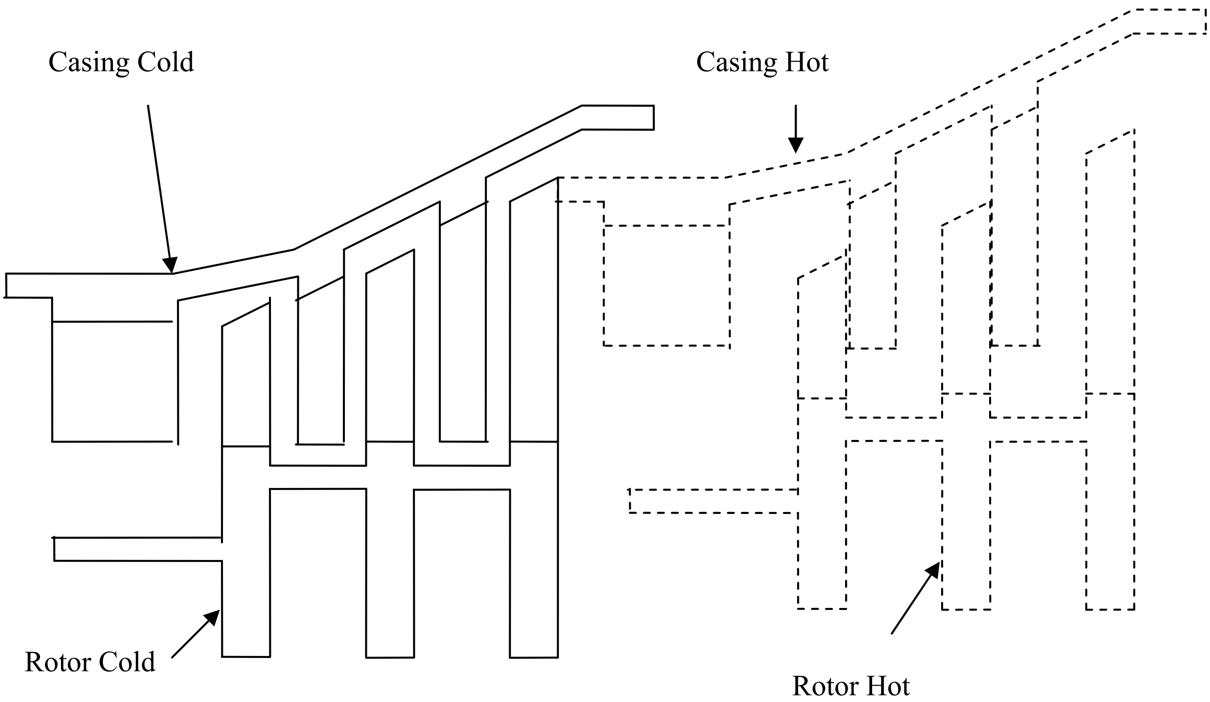

Figure 3-22: Schematic '2d' view of a Turbine showing Static and Running Positions (Movements Exaggerated for Effect).

Figure 3-22, above, shows a schematic '2d' cross section of a turbine showing both the cold (solid line) rotating and static assemblies and running positions (dashed lines).

9.6 Axial Movements

Each spool within the engine will generally only having a single location bearing that axially connects the rotating and static components. On large gas turbines it is possible for sensitive axial gaps to be a considerable distance from the location bearing and therefore large relative axial movements can exist. It is often necessary to understand the magnitude and direction of these movements so that the feature can be designed to accommodate it.