

Design Features and Procedures to Reduce the Phenomenon of HP – Rotor Bow on Jet Engines

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Abstract:

The phenomenon of thermal HP-rotor bowing after engine shutdown is a well known problem in modern jet engines. The main reason for this phenomenon is a thermal gradient between top and bottom of the rotor (and casing) caused by free air convection resulting in a thermal bending of the HP-rotor (and casing). A restart with thermal bow can result in increased vibration with the risk of rubbing HP-rotor blades into the casing. This leads to global performance deterioration. In the report the effect of thermal HP-rotor bowing is analysed.

The existence of the HP-rotor bowing phenomenon is strongly depending on the bearing concept, the design of the rotor (and casing) and on sealing arrangement of the secondary air system. Furthermore the characteristic of the engine starting and the preceding stopping cycle have a strong influence on thermal HP-rotor bowing which can significantly restrict the engine restarting capability after landing and hence lead to non compliance with the specification requirements.

In order to reduce the impact of thermal HP-rotor bowing effect on the engine it is necessary to understand the thermodynamic behaviour of the engine after shut down and the combined engine dynamic/thermodynamic behaviour during restart of the engine. Based on this understanding it is possible to include features into the engine design within the concept phase. This reduces the risk, that an unacceptable HP-rotor bowing phenomenon is detected late in the development phase. This would lead to major and expensive design changes or restart restrictions violating the engine specification.

On a typical example of a jet engine this HP-rotor bowing phenomenon has been analysed concerning the thermodynamic behaviour after engine shutdown and the engine dynamic/thermodynamic behaviour during engine restart. Based on this analytical understanding design features and engine operating procedures are discussed to reduce the impact of the HP-rotor bowing which have been demonstrated by engine test.

1. Introduction



Modern jet engines must fulfil the requirement of continuously increasing thrust to weight ratio which leads to a simultaneously higher energy density. Consequently on one hand the light weight design of the engines makes use of thin walled casings which therefore get a non-isotropic behaviour. Furthermore the design of the rotors with exception of the discs itself which have to fulfil additional requirements as e.g. life and burst margin follows the demand of weight reduction and leads to a thin walled rotor drum.



On the other hand this requirement to increase the thrust to weight ratio will be achieved enlarging the thrust capability. Therefore the overall temperature level of carcass and rotors will increase to the maximum possible according to the material specification.

In order to save fuel costs and life consumption a further demand exists to reduce after aircraft landing the number of thrust carrying engines to its minimum. Therefore many specifications require the allowance to shutdown as quickly as possible all engines after landing with exception of those which are needed to taxi the aircraft to its final parking position. This will lead to a higher global temperature level of the engine after rotor stoppage.

The phenomenon of HP-rotor bow is a result of the complex interaction between mechanics, thermodynamics (including engine installation effects) and operating conditions. Therefore all these disciplines must be taken into account to understand the physics of this phenomenon in order to take necessary precautions during concept and design phase of an engine. This will furthermore reduce the risk that an unacceptable HP-rotor bowing phenomenon will be detected late in the development phase which will lead to expensive design changes or penalties in case of specification violation.

2. Physical Mechanisms of HP-Rotor Bow after Engine Shutdown

For a long time period after engine shutdown the high power (HP-) rotor discs, but especially the discs of the HP - turbine are hotter than most of the other parts of the engine because of the big disc masses and its high temperature level during engine operation. Therefore gravity thermal convection takes place around the HP-turbine: hot air rises along all the ways which are possible due to design and concept of the secondary air system. This will in most cases happen in a non-symmetric way. During engine operation cooling air for the HP - turbine disc is flowing for a lot of secondary air system concepts along the cone behind the last stage of the HP-compressor between the combustion chamber and the HP-rotor rearwards to the HP – turbine disc (see  of figure 1). After engine shutdown the hot air will flow in the opposite direction along the HP - rotor cone according to the gravity thermal convection. While during engine operation the secondary air stream will flow symmetrically with respect to the engine axis, with no shaft rotation the air stream is unsymmetrical after shutdown especially around the HP-rotor cone (see  in figure 1). In most rotor design cases the heat transfer from bottom to the top of the HP-rotor cone driven by the gravity thermal convection around the rotor is larger than the internal heat back-transfer within the thin walled rotor cone from the top to the bottom driven by metal heat conduction according to the temperature difference. This leads to a global temperature difference between bottom and top of the rotor (and casing).

Extensive investigations concerning this temperature difference between top and bottom of the HP-spool cone were performed at MTU and confirmed the above described theoretical background. Figure 2 shows the temperature difference measured between top and bottom of a typical HP-spool cone as a function of time after engine shutdown. It can be seen that this temperature difference, i.e. bowing effect, is strongly dependent on the HP-spool speed before shutdown, i.e. a shutdown from an HP – spool speed of 75% () result in an higher bowing effect than the corresponding shutdown from 65% () for the same dwell time interval of 20 min before shut down. It should be noted that the time point of maximum temperature difference is about 90 min after engine shutdown, which is nearly independent from the HP-spool speed level before engine shutdown. After a time period in the range of 6 hours the HP-rotor is

cooled down and the phenomenon of HP-rotor bow vanishes. Thermal analysis simulating this non – symmetric heat transfer phenomenon after engine shutdown performed at MTU (see figure 3) resulted in an excellent confirmation of the measured temperature differences of figure 2. For the model the big mass and high temperature level of the HP-turbine disc as main heat source is taken into account. Therefore it can be concluded that the temperature difference between top and bottom of the HP-spool cone is strongly correlated to the absolute temperature level and temperature dependence over time of the HP-turbine after shut down.

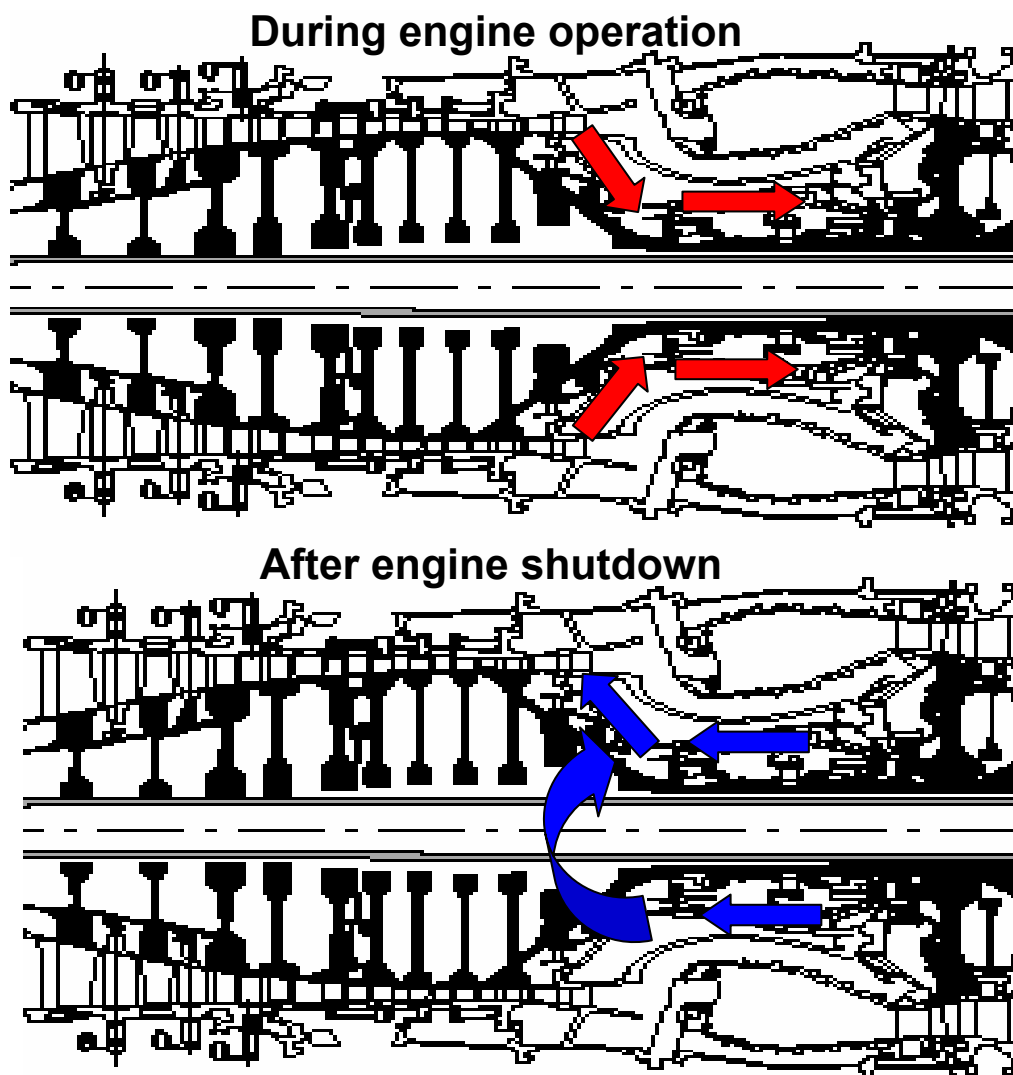


Figure 1: Secondary airflow of a typical jet engine during engine operation and after engine shut down

This temperature difference between top and bottom of the HP-rotor will lead to the well-known thermal bowing effect of the spool and casing. Relative displacement measurements between HP-spool and casing were performed at MTU. The HP-rotor was turned by hand at the time point of maximum temperature difference (90 min after engine shut down) and showed an eccentricity in the mid of the HP-spool of about 0.07 mm. In some extreme cases the bowed HP-rotor even sticks within the casing a certain time period after shutdown and therefore prevents an engine start without damage on tips an abradable coating.

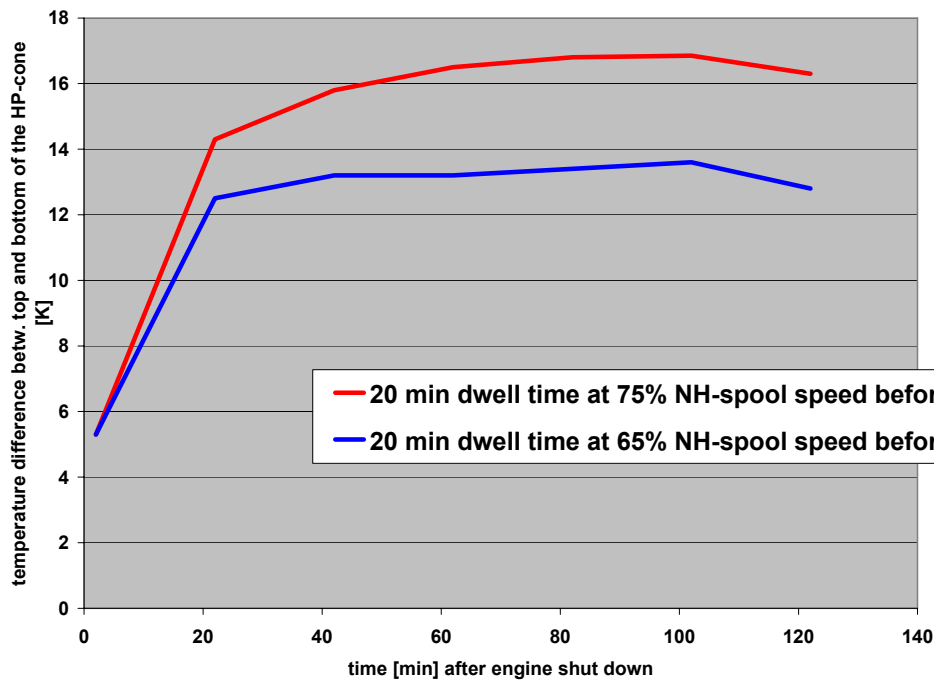


Figure 2: Measured temperature difference between top and bottom of the HP-cone after different shutdown conditions.

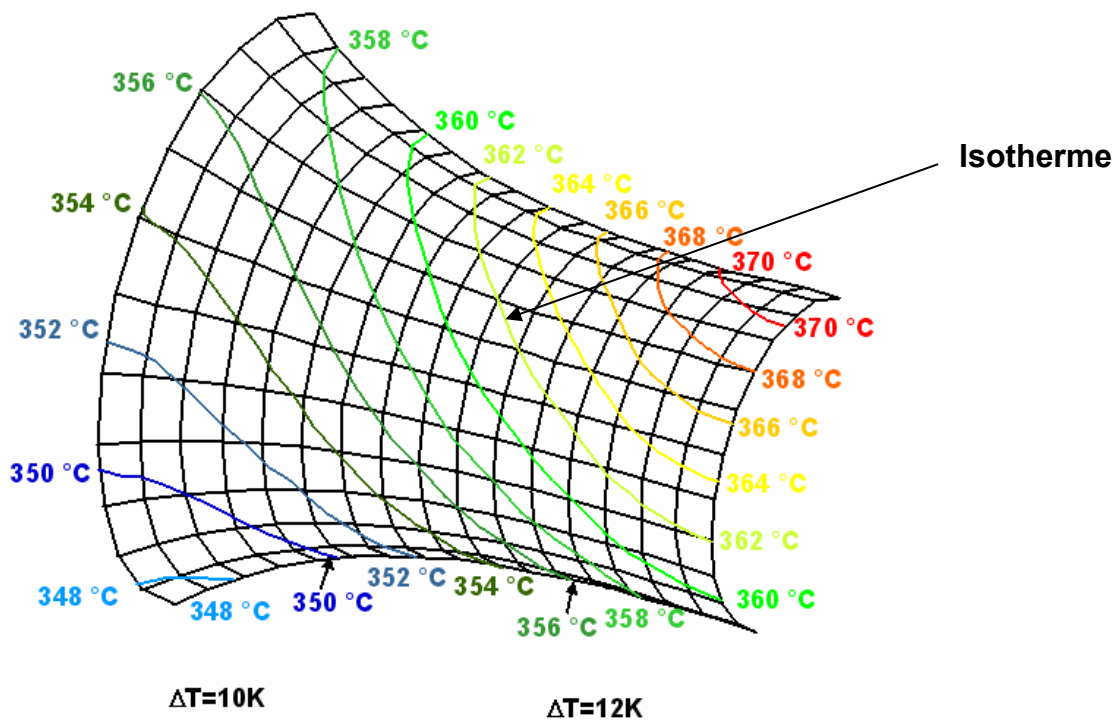


Figure 3: Model and thermodynamic results of an HP-rotor rear cone after engine shutdown

3. Physical Understanding of HP-Rotor Bow during Engine Restart

If the HP-rotor bowed by its thermal gradient between top and bottom is restarted, it behaves similar to a rotor with a geometrical imperfection (like the swash of a rotor flange or coupling) and rotates around the fixed rotor points on the bearings (see figure 4). This thermal HP-rotor bowing together with a possible thermal deformation of the casing can lead to unwanted rubbing of the HPC-tips against the casing, i.e. permanent tip clearance increase which results in performance deterioration and/or surge margin loss. In extreme cases this can result in a heavy damage of the blade tips.

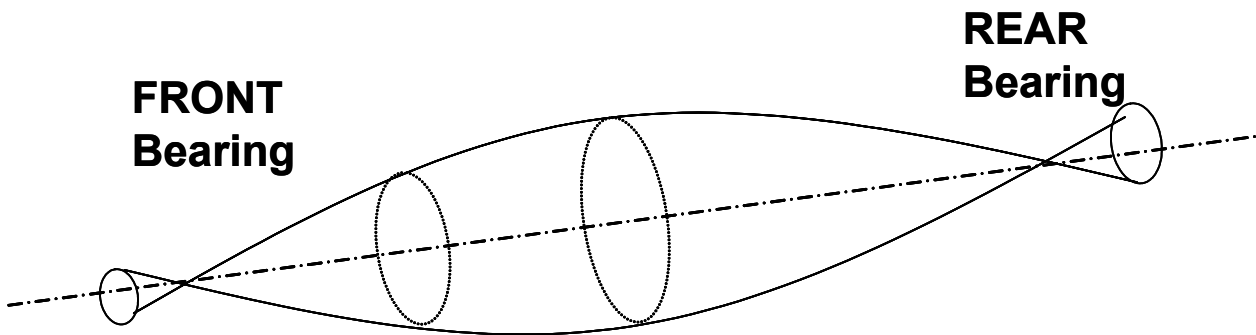



Figure 4: Schematic plot thermal bowed rotor

During restart the rotation of the thermal bowed rotor creates in rotating loads on the bearings which are varying with HP-spool speed. Therefore from vibration point of view the structure responds with the 1st engine order of the rotor speed which is similar to the vibratory response caused by unbalance.

The HP-rotor of some aero engine types are supported on its front end by a flexible element (squirrel cage) combined with a squeeze film damper to influence its critical speeds for normal operation. Using this design feature a low-damped fundamental critical speed (bending mode) of the HP-rotor can be replaced by a damped HP-rotor bounce mode. If during restart the rotating bearing loads, which are caused by the thermal bowed HP-rotor, are high enough, the orbit of the rotor at bearing position bridges the squeeze film of the squirrel cage. This squirrel cage is out of function and the HP-rotor changes its critical speed to the fundamental bending mode. For some engine types this bending mode is below idle. A restart of a thermal bowed rotor can then result in a strong increase of vibrations and the risk of unwanted heavy rubbing of the HP-rotor against the casing due to the amplification effect of the critical speeds.

During the restart itself the air stream along the rotor (see figure 1 ) flows again symmetrically around the engine centre line and the temperature gradient between top and bottom of the HP-rotor cone decreases. This effect is strongly dependent on the heat transfer coefficient between air stream and rotor drum and increases with rotor speed and air stream velocity. Therefore there exists the possibility that the thermal bowing effect at idle is strongly reduced or already gone.

4. Dependencies on Thermal HP-Rotor Bow

As explained in the paragraphs above the phenomenon of HP-rotor bow is an effect of the interaction between thermodynamics and engine dynamics. In this paragraph the dependencies on

the thermal HP-rotor bowing effect will be discussed, which can be divided into two categories, the thermodynamic and design items.

One of the thermodynamic dependencies is the global absolute temperature level of the HP-turbine disc after shut down. This absolute temperature level will determine the maximum achieved relative temperature difference between top and bottom of the HP-rotor during standstill. It can be influenced by the idle conditions before shut down. The absolute temperature level of the HP-turbine disc at idle conditions is characterized by the level of the HP-rotor speed and the dwell time at idle before shut down, which is acting as cooling down effects. Figure 5 shows a comparison between calculation and test results performed by MTU. For this study the absolute HP-turbine-disc temperature was calculated for the NH- speed profile marked as ■■■■ in figure 5. At time point 0.0 it reduces rapidly from max power to various speeds (75%/70%/65%) from which a shutdown can be performed. The corresponding calculated HP-turbine disc temperatures for the various speeds are plotted in ——— for 75%-speed, in ——— for 70%-speed and in ——— for 65%-speed. If the engine will be switched off after a certain dwell time, the absolute HP-turbine disc temperature at rotor standstill is then proportional to the corresponding temperature from which the shutdown was performed. Corresponding engine restart tests revealed that the existence of high vibrations during restart (marked as ⊕ in figure 5) is strongly dependent on the absolute temperature level of the HPT-disc at idle after shutdown. Below a certain threshold temperature (in this case a normalized HP-turbine-disc temperature of about 0.42) only low vibrations were found (marked as ☆ in figure 5). Figure 5 additionally shows that engines using high HP-rotor idle speed tend to show high vibrations during restart which cannot be compensated even by a long dwell time at idle.

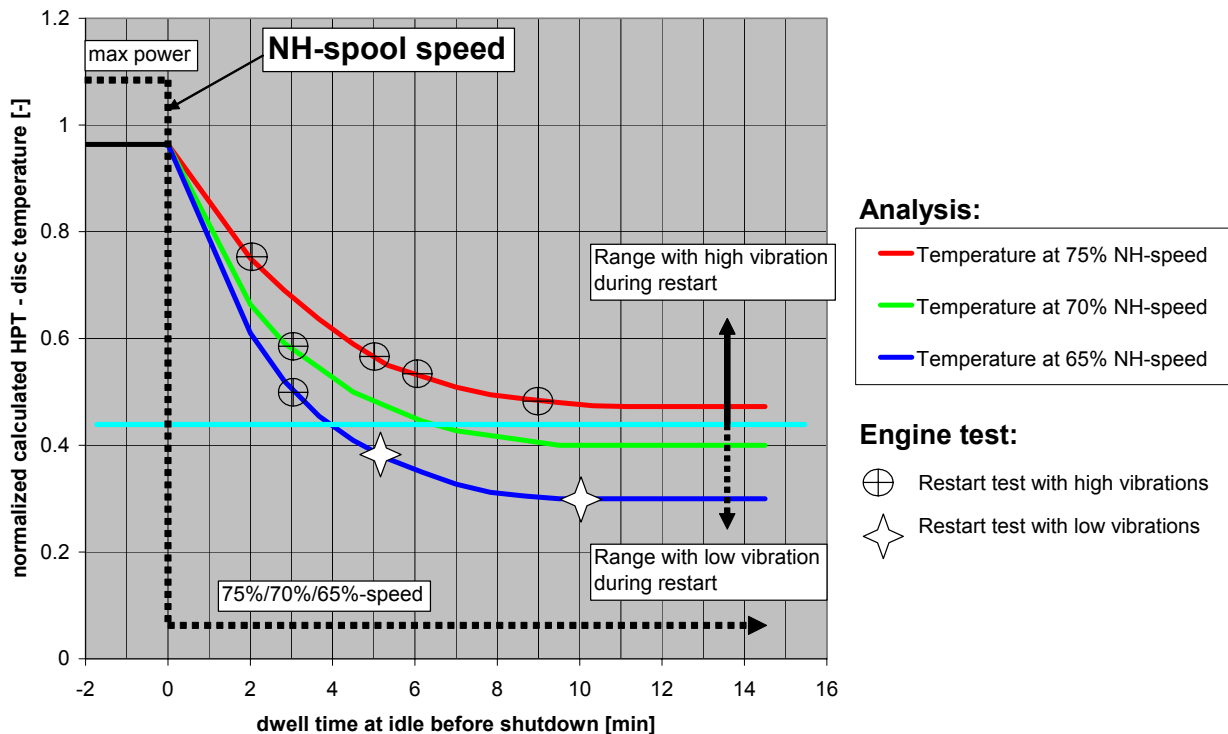


Figure 5: Dependency of vibrations during restart on overall temperature of the engine (HP-turbine disc)

The second thermodynamic dependency is the thermal gradient between bottom and top of the HP-rotor which arises after engine shut (as described in para. 2) because of thermal mismatching between gravity thermal convection around the HP-rotor cone and heat conduction within the HP-rotor cone structure. Therefore the intention must be to balance both thermal heat transfer features. On one hand the possibility exists to increase the heat conduction within the HP-rotor cone. On the other hand a reduction of air stream around the HP-rotor cone can significantly reduce the risk of vibrations during restart (see paragraph 5).

From design point of view the definition of the bearing concept of the HP-spool has an additional impact on the vibration behaviour of a bowed rotor during restart. Figure 6 shows the most common bearing concepts of an HP-rotor. Whereas the bowed HP-rotor which is supported on both ends acts more like a static unbalance, the bowed HP-rotor, whose rear bearing is located between HP-compressor and HP-turbine will be more loaded by a couple. Depending on the rotor parameter length, stiffness and mass distribution along the rotor the individual rotor concepts can have a major contribution to the existence of high vibrations during restart and must be separately analysed for each specific rotor in detail.

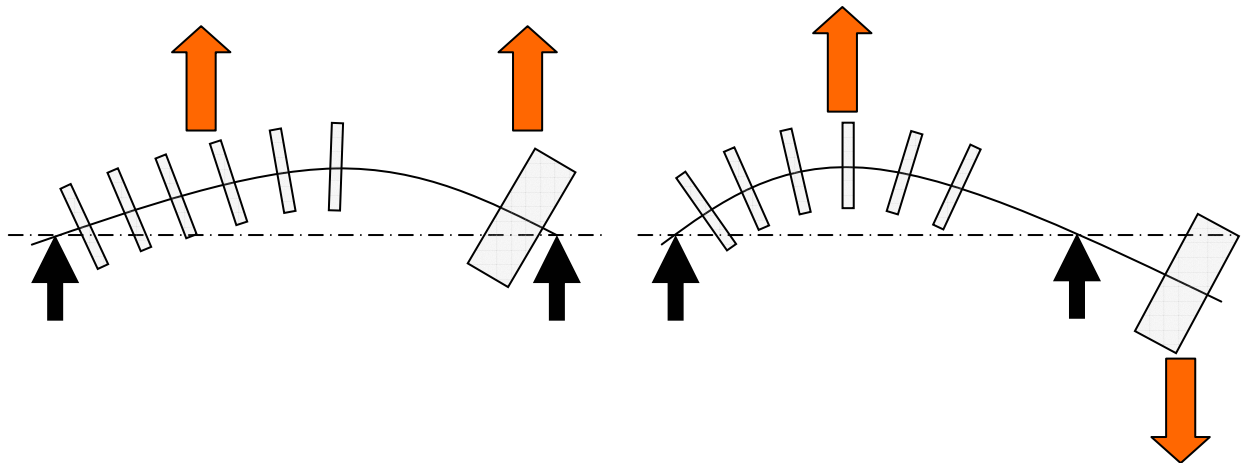


Figure 6: Bearing concepts of common HP-rotors and their impact on thermal HP-rotor bow

5. Procedures and Design Features for Thermal HP-Rotor Bow Reduction

Taking into account the general understanding of phenomenon described in para. 4 the following features can be influenced in principle:

- a) Change of relation between heat conduction within the HP-rotor cone and gravity thermal convection around the HP-rotor cone
- b) Reduction of absolute temperature level of the engine (i.e. HP-turbine disc) after shutdown
- c) Equalization of circumferential HP-rotor temperature profile after shutdown and during engine restart
- d) Reduction of air flow caused by gravity thermal convection after engine shut down

The following chapters describe how these features can be influenced:

Change of relation between heat conduction within the HP-rotor cone and gravity thermal convection around the HP-rotor cone

The relationship between heat conduction within and gravity thermal convection around the cone can be improved by an increase of the circumferential heat back-transfer within in HP-spool cone. This is achievable by the change of the HP-spool cone material to another one with a higher heat conduction factor or by the increase of thickness of the HP-rotor cone (note: this thin cone is suggested to be the most sensitive area concerning temperature difference, i.e. HP-rotor bow). The second possibility would only result in a significant improvement in case that the wall thickness of the HP-rotor cone heavily increases. This strongly conflicts with the mass requirement for aero engines and can therefore be introduced in stationary gas turbines.

Reduction of absolute temperature level of the engine after shutdown

The absolute temperature level of the HPT-disc is suggested to be one of the main root causes of the HP-rotor bow phenomenon. The big mass and high temperature level of the HPT disc is the main and longest heat source after shutdown which leads to thermal gravity convection. A decreased temperature level can be obtained by a reduction of the HP-spool speed at idle to a possible minimum according to the performance requirements (see also figure 5). Another possibility is to increase the dwell time at idle before engine shut down to the maximum allowed by the engine specification in order to elongate the cooling effect. Both possibilities were tested on a typical aero engine. Figure 7 shows for two dwell time periods (5 min — and 10 min —) the dependency on engine vibrations for different NH-spool speed levels before engine shutdown. It can be shown that the engine vibrations grow exponentially with increased NH-spool speed before

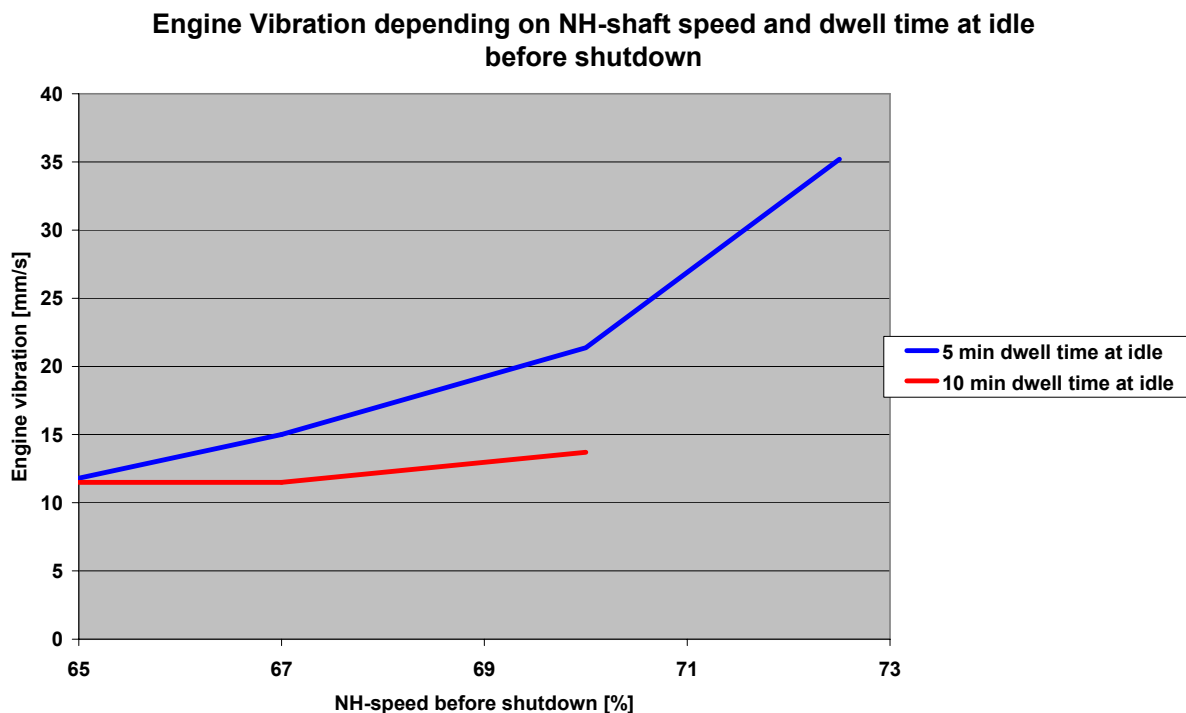


Figure 7: Engine vibration dependency on NH-spool speed before engine shutdown

shutdown. Figure 8 shows for one NH-spool speed (in figure 8: 70%NH-spool speed) the dependency of measured engine vibrations on dwell time intervals before shut down. This reveals that the cooling down effect described in para. 4 is satisfied from a defined dwell time before shutdown onwards, in figure 8 for dwell time intervals higher than 10 min.

Engine Vibration dependance on different dwell time intervals at idle before shutdown

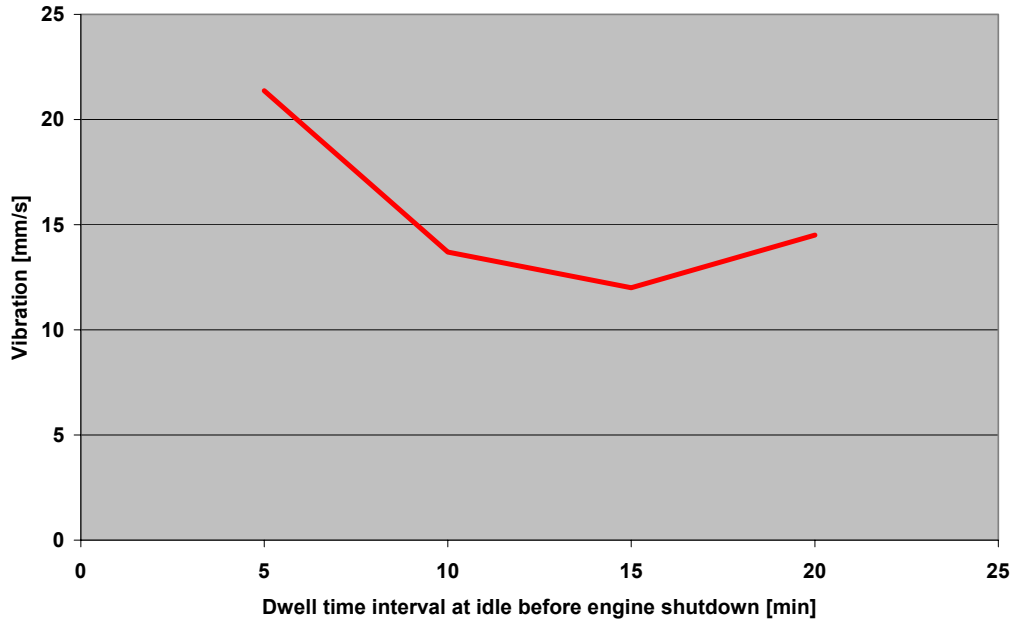


Figure 8: Engine vibration dependency on dwell time interval of NH-spool speed before engine shutdown

Equalization of circumferential HP-rotor temperature profile after shutdown and during engine restart

The equalization of the growing temperature difference between bottom and top of the HP-spool after engine shutdown can be obtained by a slow and continuous rotating HP-rotor or by 180° turns of the HP-rotor performed after defined time intervals. This procedure is already installed in some aero engines,

but it needs additional installation effort i.e. an increase of mass on gears, couplings, motor and additional power supply and control for the HP-rotor rotation after shutdown.

Another possibility for this task is to perform just before the engine restart one or more so-called dry cranks, i.e. an engine start without fuel injection powered only by the auxiliary power unit up to an HP-spool speed, which isn't detrimental to the engine concerning bowing effect, and a start abort. This procedure, although it is very effective, is not welcome by the airlines and therefore mostly not practicable. A further way to equalize the circumferential temperature profile can be achieved during engine start. Figure 9 shows as an example the behaviour of engine vibrations (thick lines —, —) for two types of HP-spool speed profiles during restart (thin lines —, —). It can be seen that a small elongation of starting time can significantly reduce the vibration level during start. This additional time interval will be used to reduce the bowing effect at an HP-spool speed range which is not detrimental to engine. Therefore this procedure is a combination between

dry crank and normal restart, i.e. an appropriate starting logic, which helps to reduce vibrations during restart.

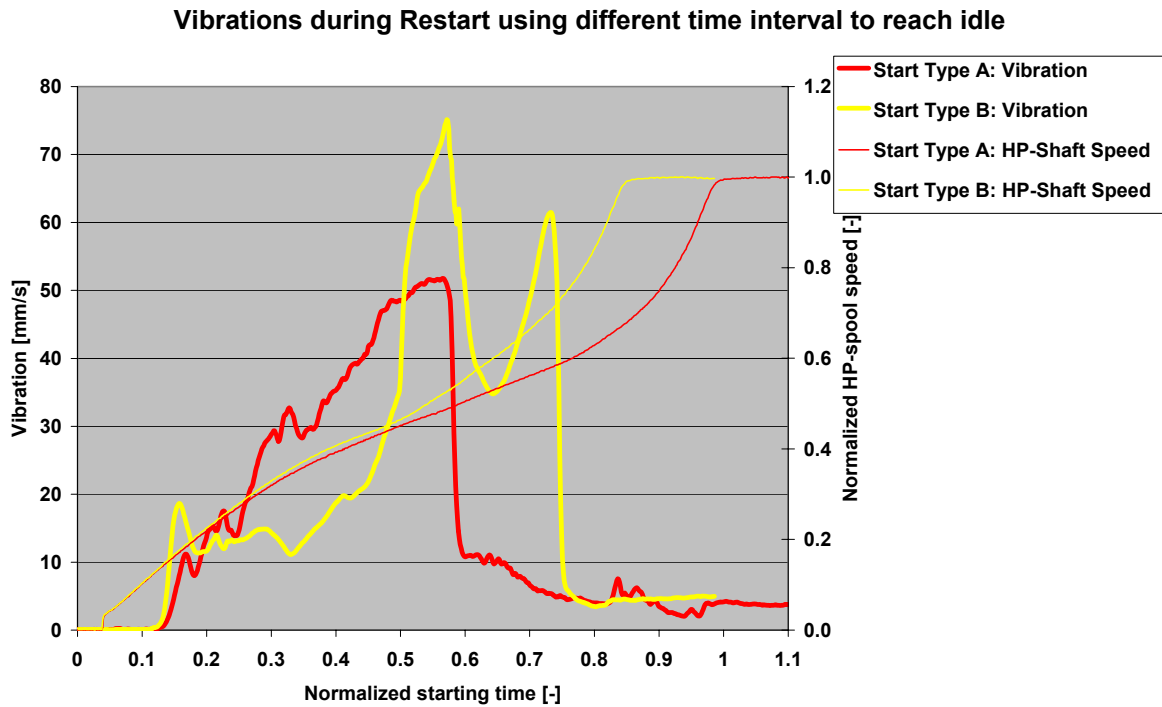


Figure 9: Engine vibration dependency on start time interval and NH-spool speed profile during restart

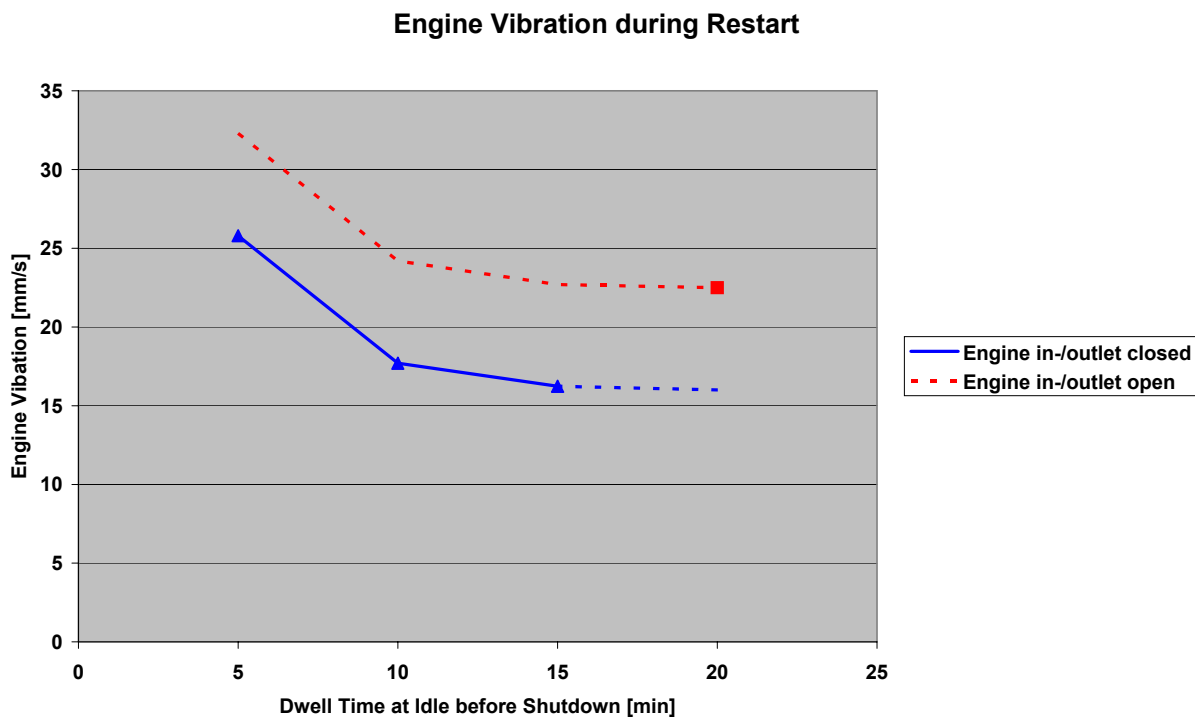




Figure 10: Engine vibration during restart after different dwell time at idle before with closed/open engine in- and outlet

Reduction of air flow caused by gravity thermal convection after engine shut down

A reduction of the air flow caused by the gravity thermal convection after engine shut down is achievable in different ways. One possibility is to restrict the total air flow through the engine. MTU have performed engine tests comparing restarts using two configurations: in one configuration the total amount of air was reduced closing immediately after shutdown the engine inlet and outlet, in the other configuration no closing procedure was applied. Figure 10 shows the results of these tests for different dwell times before engine shutdown. The line marked with  represents the vibrations resulting from the tests with the open inlet/outlet, while the line marked with  shows the results of the corresponding tests with closed engine ends. On the tested engine type a vibration reduction of about 7mm/s was achieved.

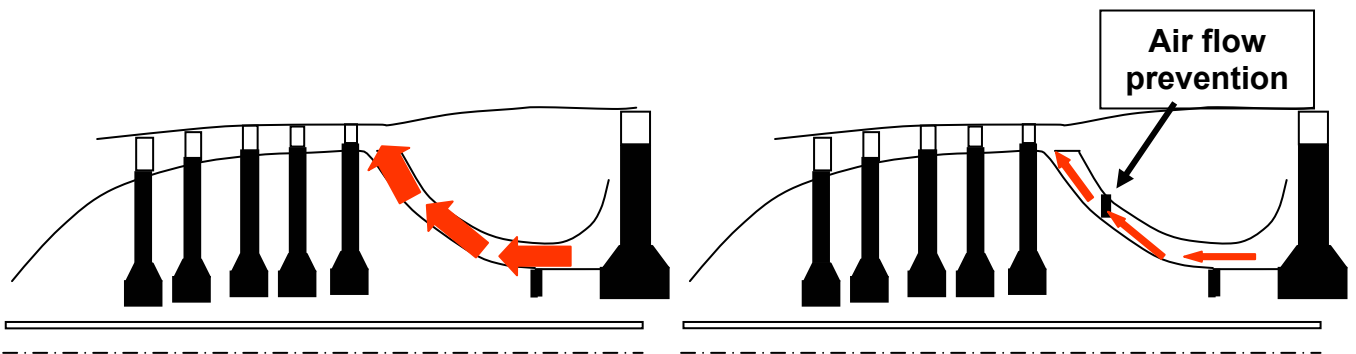


Figure 11: Engine configuration with/without sealing on the HP-spool cone behind the last stage of the HP-compressor

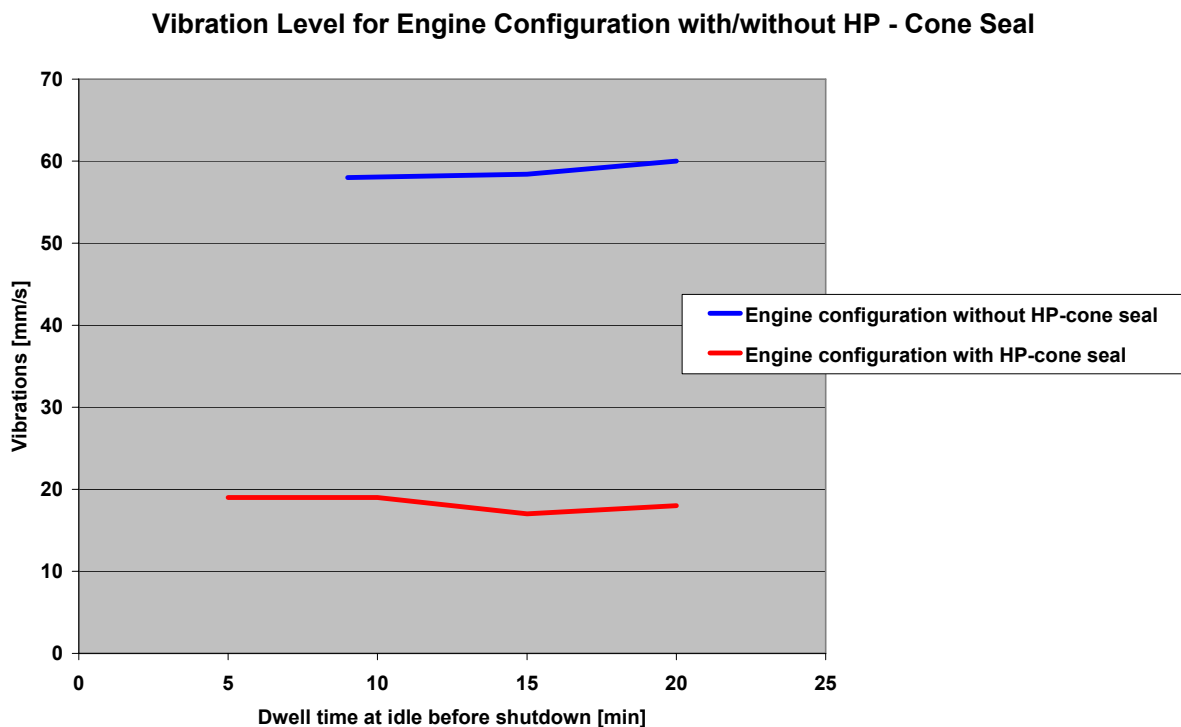


Figure 12: Engine vibration during restart after different dwell time at idle before with different seal arrangements

The most significant effect in vibration reduction during restart can be achieved if the air flow caused by gravity thermal convection after engine shutdown is strongly reduced, especially along the sensible HP-spool cone behind the last stage of the HP-compressor (see also para. 2). This is feasible by introducing an air stream restrictor which prevents the air to flow back after engine shutdown. Figure 11 shows a principle configuration of such a restrictor which is part of the sealing arrangement, and therefore this has to be defined during the concept phase of the secondary air system. The most appropriate seal type would be a brush seal which is at zero speed in contact with the HP-rotor. This brush seal is then acting as a “curtain”. Both configurations, with and without air flow prevention, were tested at MTU in detail. Figure 12 shows a comparison of engine vibration measured during restart as function of dwell time at idle before shutdown between the engine configuration without HP-compressor cone seal (—) and with sealing arrangement (—). A significant reduction in vibrations to about one third by implementing this HP-spool cone seal arrangement was achieved for the tested engine type.

6. Summary

Based on the fundamental physical understanding of the well known thermal HP-rotor bowing phenomenon in jet engines and on large experience achieved during engine test at MTU it is possible to establish engine operating procedures and design features to prevent a thermal HP-rotor bow problem accordingly. These features can be introduced a priori to reduce the risk of performance deterioration achieving unacceptable vibrations during restart. Therefore major and expensive design changes or restart restrictions violating the engine specification can be avoided.

After engine shutdown a thermal gradient between top and bottom of the HP-spool (and casing) grows up caused by gravity thermal convection around the thin walled HP-cone behind the last stage of the HP-compressor whose internal heat conduction is slower. Driver for this convection is the temperature of the HP-spool discs, especially the HP - turbine discs, which is from its mass and temperature point of view the largest and longest remaining heat source after engine stoppage.

Therefore most of the possible changes on engine operating procedures to reduce the impact of the thermal HP-rotor bowing are aimed to reduce the remaining absolute temperature level of the HP-discs after engine shut down. The objective of possible restart procedures is to reduce the thermal circumferential gradient of the HP-rotor (and casing) at low speed during which the effect in unacceptable engine response is minor. In most cases these engine operating procedures are limited by the specification requirements.

The most effective design feature restricts the air flow caused by thermal heat convection around the HP-cone behind the HP-compressor after engine shut down. This is possible by a definition of the secondary air system which needs a brush seal at this region. As this brush seal remains in contact with the HP-spool at zero speed it will stop the heat flow back after engine shutdown caused by thermal gravity convection. Engine tests performed at MTU with the configurations – without and with HP – cone brush sealing arrangement – showed that the vibration effect during restart can be significantly reduced, i.e. a factor of 3, by introducing a brush seal at this position.