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Validation of the Booster Bleed Valve Control Logic in the New BR715 Jet Engine

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ABSTRACT

The subject of this paper is the validation of the newly developed booster bleed valve control logic, which has been implemented into the new BR715 turbofan jet engine.

The booster compressor is protected from surges in the low power regime as well as during transient operation by opening a booster bleed valve. This bleed valve is situated just after the booster compressor and passes bleed air into the bypass duct, hence unloading the booster compressor in critical operational conditions. The BR715 jet engine takes advantage of a newly developed logic driving this valve. Monitoring input parameters such as spool and flight speeds as well as altitude, the combined steady state and transient logic provides the capability of appropriately positioning the valve. This ensures maintaining an optimum performance of the engine throughout the whole operating range. Furthermore the logic allows for reaction on special requirements such as surge events.

During testing for certification of this engine, extensive handling tests have been performed. The performance of the logic was investigated in detail and the results are documented within this paper. They prove the logic to be working very successfully. The booster compressor is totally protected from surge in the low power regime during steady state conditions. For transient operation, especially during rapid decelerations as well as during bodie manoeuvres of the engine, the core logic for the transient modulation showed extremely effective behaviour.

The various schedules inside the logic were partially varied for testing. This paper comprises this development process and each table's contribution to the booster compressor's behaviour is explained in detail.

NOMENCLATURE AND ABBREVIATIONS

ALTC	Altitude Computed
ATF	Altitude Test Facility
BBV	Booster Bleed Valve
CLSM	Control Laws Simulation Model
EEC	Electronic Engine Controller
FADEC	Full Authority Digital Engine Control
IPC	Intermediate Pressure Compressor
HP / LP	High Pressure / Low Pressure
MNC	Mach Number Computed
P20V / T20V	Total Fan Inlet Pressure / Temperature Validated
P30V	HPC Delivery Pressure Validated
STF	System Test Facility
VSV	Variable Stator Vanes

INTRODUCTION

The BR715 turbofan is a modern two spool aeroengine, designed to power aircraft of up to 100 seats. Compared to the smaller BR710 engine, powering business jets, an increase in thrust was required, leading to the demand of higher core pressure. Therefore the BR715 engine features a booster or intermediate pressure compressor (IPC). Since the IPC is adapted to the LP shaft, its speed is equal to the fan speed. The mass flow through the IPC on the other hand is dictated by the mass flow accepted by the following high pressure system.

This is a difficult environment for compressors, since they are always driven in an optimum operating point close to the surge line. If the HP system is decelerated, the operating point of the IPC moves immediately towards the surge line. Due to the narrow surge margin, the compressor would surge rapidly. This would lead to thrust loss and overheat of the whole engine, in worst cases even to safety hazards.

To compensate for the rise of the operating point during transient manoeuvres, a bleed valve has been introduced between IPC and HPC. It has a similar effect as a bleed in the aft stages of the HP compressor (HPC): protection against surge and ease of recovering from surge.

The BR715 engine is controlled by a FADEC system including an Electronic Engine Controller (EEC). All logic needed to drive the engine, such as the control logic to schedule the Booster Bleed Valve (BBV) are contained in the EEC. It has been developed from synthesis and first engine tests (Peitsch et. al. 1998) and is based on signals available from the production instrumentation. During the certification process for the BR715 engine, this logic had to proof its functionality and performance. Tests have been conducted on sea level testbeds as well as on an altitude test facility. Improvements to the involved schedules have been performed based on the results of these tests. The discussion of the used validation strategy for the stability of the IPC and the BBV modulation logic are the subject of this paper.

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COMPONENTS OF THE BBV MODULATION LOGIC

The total booster bleed demand, i.e. the area demanded open, is split up into a part for steady state operation and a more complex part for the transient handling of the engine. The conventional way to schedule the compressor bleed valve during steady state operation is basically according to LP spool speed N1 corrected to the total upstream temperature T20V. Additional parameters in the current logic are the computed flight Mach number MNC and the flight altitude ALTC. The latter influence was regarded as a backup feature, but ATF testing has proofed no requirement for this schedule.

The initial schedules have been set up by parameter variations within transient simulations without bleed valve opening. They are found by the definition of a minimum surge margin. Basically, high bleed flows are required in idle conditions to improve the narrow surge margin in this region. In high power settings no steady state demand is scheduled.

The transient modulation control shall on the one hand side protect the booster compressor stability by maintaining a minimum surge margin during all manoeuvres irrespective of flight condition, power level and rate of change of power level. Furthermore it shall operate without oscillation of the BBV position during transient engine operation, especially with respect to the beginning and the end of a manoeuvre.

The main parameter for a transient BBV modulation has been chosen to be the HPC outlet pressure P30V. It is one of the first parameter in the logic chain indicating, that a change in power level is taking place. So the lagged derivative is taken as input to the transient control logic. To make it more independent from the power level of the engine, it is nondimensionalized by itself.

A more complex lag is then applied to this differential to ensure, that the signal is transferred to the downstream control process rapidly in case of a deceleration and slowly in case of a subsequent re-acceleration (reslam manoeuvre). This logic ensures not to slam the BBV closed during this scenario, because this would immediately cause large working line excursions.

At higher altitudes, jet engines tend to be sluggish due to the low density of the ambient air. This leads to an increase of the response time during transients compared to the constant cycle time of the control logic. So the control logic has to be moderated with respect to time. Hence the delta total fan inlet pressure (P20V/14.696 psi) is used as a separate input to the time constant for the above lag.

The result coming out of this lag procedure is used together with ALTC to account for Reynolds number effects to schedule the transient BBV offset. This is finally added to the steady state demand, giving the demand for normal operation of the engine.

The logic also takes care of special events. Engine tests have proven, that introduced features such as a BBV reset for thrust reverser deployment and foreign object damage (FOD) are not required. Nevertheless, the surge detection logic is used to schedule the BBV partially open in case of an HPC surge. The surge detection logic has been included in the BR700 series control logic in order to open the handling bleed valves of the HPC and hence aid in recovery from surge. The logic is based on the rate of change of the P30V signal. If P30V drops rapidly and the reason is not a reduction in fuel flow (i.e. during deceleration of the engine) a surge is assumed to have happened. An HPC surge can also be caused by a preceding booster compressor surge, so in any case, it is helpful to open the BBV.

Parameter	Resulting Component
N1 T20 MNC	Steady State BBV Demand
P30 P20 ALTC	Transient BBV Demand
Surge Detection Flag	BBV Reset for Surge Recovery

Table 1: Components of BBV Modulation and Influencing Parameters

For a summary of the realized BBV modulation components as well as the influencing parameters, see Table 1. A rate limiter is implemented to restrict the rate of closing, whilst leaving the rate of opening effectively unlimited. Both rate limits are dependent on altitude to additionally cover the response time issue mentioned above.

The following summary can be given concerning the schedules and factors affecting the modulation of the BBV:

- Basic Steady State Schedule = f(N1RT20, MNC)
- Basic Transient Schedule = f(P30 Change, ALTC)
- Schedule for Time Constant of Transient Lag Function
- Rate Limiter Schedules = f(ALTC)

The next section shows, how these schedules and parameters have been derived and which strategy was used to validate the logic and proof the booster compressor to be free from unacceptable surge risks.

SETUP OF SCHEDULES AND VALIDATION STRATEGY

Beside experimental testing of a jet engine, its development is based on complex synthesis programs. For BMW Rolls-Royce engines, the Rolls-Royce Aero Engine Performance Program (RRAP) is used. The modular setup of this program enables steady state investigations as well as transient simulations very easily. At the beginning of the development process, a synthesis deck was set up with an estimated booster compressor surge line. Several computations have been performed on different engine power levels around the flight envelope in order to set up a proper steady state schedule. No credit was taken on any BBV being present. At those flight conditions, where the operating point of the booster compressor was beyond respectively in the vicinity of the surge line, the required opening for an appropriate unloading of the booster compressor was calculated. This lead to a minimum required geometric area on the one hand side, but also already to an initial steady state schedule for different power conditions.

For the transient schedule, slow and rapid decelerations as well as reslam manoeuvres have been simulated at different altitudes and flight speeds. A slam deceleration is obtained by slamming the throttle from the maximum to the minimum position. For reacceleration, the throttle is moved back to the maximum position again ('reslam'). It is assumed, that the highest working line excursions appear during these manoeuvres. A simplified EEC simulation logic was used in the beginning, which was replaced by a more sophisticated control laws simulation model (CLSM) during the development process of the logic itself (for details, see Peitsch et. al. 1998).

The stability of the IPC has to be proven during certification

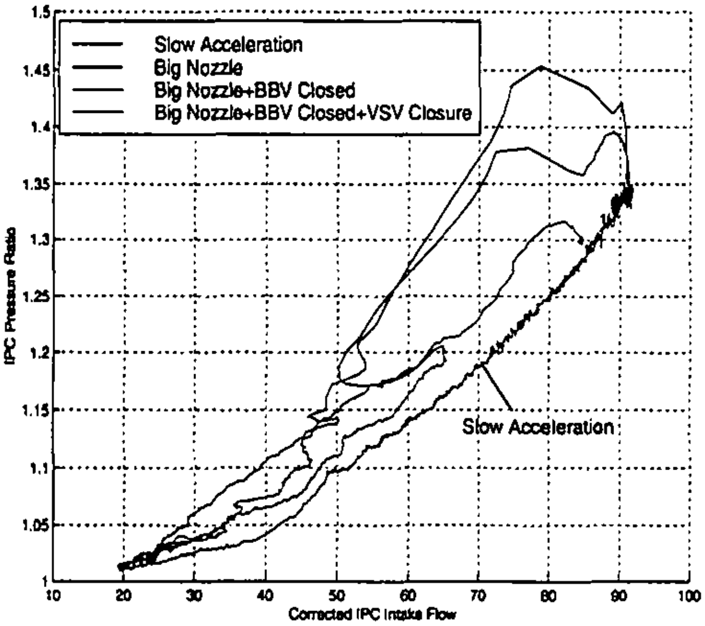

Fig. 1: Means for Validation of Surge Margin

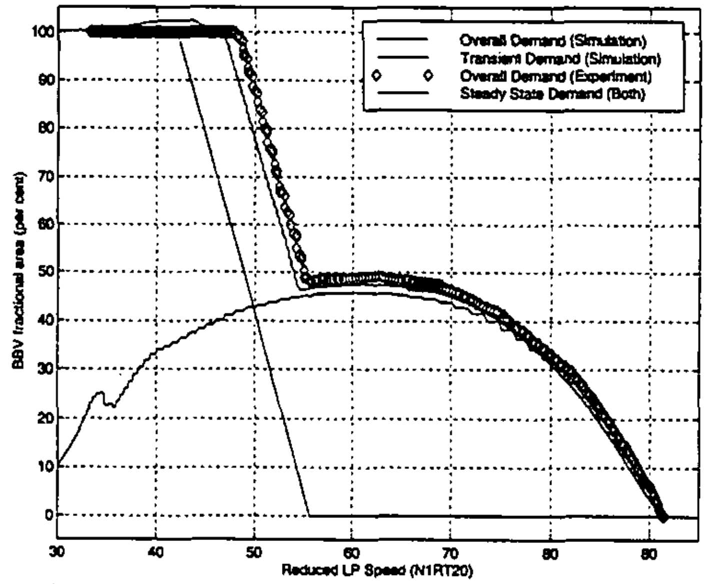

Fig. 2: BBV Demand for a rapid Deceleration (Original)

testing to fulfill the authorities' requirements. These tests can also be regarded as a mean for gaining confidence in a proper working of the BBV modulation logic.

Stability tests can be used to find out the surge margin of a compressor. The surge line shall remain unaffected for a given flight condition, thus the working line of the compressor has to be rised artificially. Since low pressure compressors in a jet engine have a different behaviour compared to HPCs, they also need different approaches:

- Use of a development engine featuring a turbine of reduced capacity. Bleed extraction is used in this case to stabilize operation at high power settings. Starting from high power, a slow deceleration is performed, until the surge line is reached. This may be repeated with various bleed extraction rates to map out the surge line.
- Fit a bigger exhaust nozzle to the engine. This increases the expansion ratio of the LP turbine, causing a rise in LP spool speed at a core massflow.
- De-Spike the engine, i.e. decrease the fuel flow rapidly in order to get a fast rundown. This translates to a stronger deceleration of the engine than in normal handling scenarios.
- Close the Variable Stator Vanes (VSVs) rapidly. This causes the IPC to be throttled back due to the reduced mass flow accepted by the HPC.

These measures assume a normal operation of the BBV. It is possible to overwrite the valve to remain closed all the time, which causes an amplification of the working line rise. For the handling tests on the BR715 engine, the last three measures have been investigated in a single as well as in a combined way, even with the BBV overridden closed in order to clear sufficient surge margin of the booster compressor. The influence of these on the working line of the booster compressor is shown in Fig. 1 in a qualitative manner. The figure shows the resulting working lines in terms of IPC pressure ratio vs. Corrected intake mass flow. The lowest working line was taken as a steady state reference coming out of a very slow acceleration. All other included lines are coming out of rapid decelerations of the engine.

Fitting just a bigger exhaust nozzle to the engine gives a first rise in terms of working line. However, a much bigger rise is achieved by additionally closing the BBV. This even leads to a surge in the power region. Additionally moving the VSV position increases the cleared pressure ratio in the high power region and was thus be used to clear the booster compressor's surge margin there.

RESULTS

The BR715 engine has been undergone extensive testing on various testbed in the certification process. These tests were split into sea level static tests mainly in Dahlewitz/Germany and tests on the Altitude Test Facility (ATF) in Pyestock/England. This section describes, which of the handling tests revealed problems with the BBV modulation logic and how these problems were accommodated.

Sea Level Testing

First tests for the general handling of the BR715 engine have been performed on the BRR sea level testbed in Dahlewitz/Germany.

These tests have been also used to check the stability of both the compressors (IPC and HPC) with the original BBV modulation logic and numbers incorporated. During rapid decelerations, a first anomaly was seen concerning the slope of the BBV area demanded versus speed respectively time. Fig. 2 shows the original slope of BBV position vs. Corrected LP spool speed. The symbols show the logged actual BBV position during the test. It involves a kink in the middle of the manoeuvre.

The origin of this kink was found to be the combination of transient and steady state demand. Since they have not been logged during testing, both are included in the figure coming out of a transient simulation using the CLSM. The *transient demand* is mainly dependent on the rate of change of P30V, which is very high at the beginning of a rapid deceleration as given here. Hence, the BBV

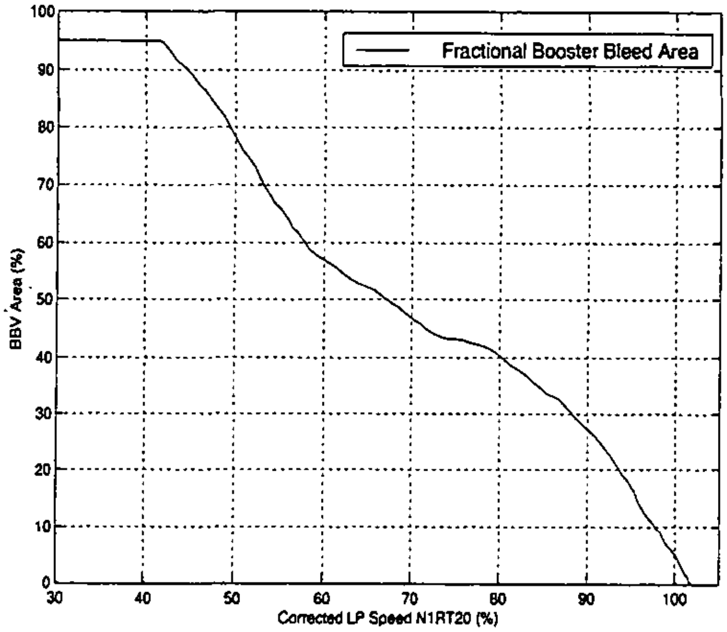

Fig. 3: BBV Demand for a rapid Deceleration (Optimized)

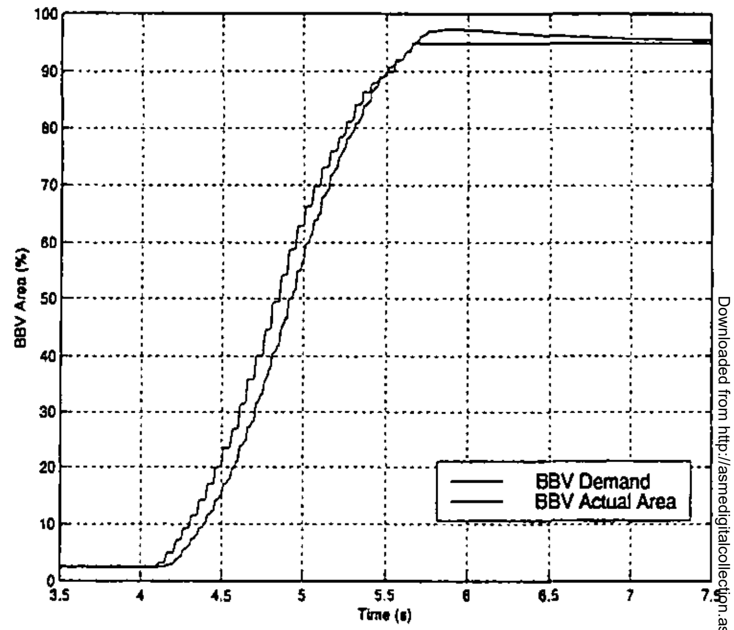

Fig. 4: BBV Opening Rate Limiter Impact

demand increases rapidly at high speed. The rate of change of P30V is decreasing through this manoeuvre, so the transient demand reaches a maximum value and is reduced again. The *steady state demand* in these sea level static conditions is only dependent on the corrected speed. It comes into effect starting at values of 56%. The initial schedule increased the demand linearly, while speed decreases. If the overall demanded BBV area is compared between test and simulation, it can be concluded, that the BBV logic works like it was expected.

However, since both demands are summed up to give the BBV position demand, the kink shown above is the result. Since during a smooth manoeuvre, a smooth behaviour of the BBV position should be expected as well, the steady state schedule had to be optimized. This was done by flattening the whole schedule as well as by smoothing it at the begin and the low and the high ends. This leads to an earlier opening of the BBV with respect to corrected speed, hence taking over earlier from the initial transient demand.

One of the boundary conditions during this change was to keep the schedule nearly independent of the Mach Number for low speeds. This condition comes out of the fact, that the determination of the Mach Number is based on the ratio of total over static pressure. For existing pressure probe accuracies, this determination is difficult for small flight speeds, leading to varying Mach Numbers. If a strong dependency of the BBV on Mach Number would be involved, the BBV demand would follow an inaccurate Mach Number.

The result of the optimization in terms of BBV demand for a rapid deceleration can be seen in Fig. 3. It shows the behaviour of the actual BBV area vs. Corrected LP spool speed for the same manoeuvre as in Fig. 2, but starting at a different power condition. Although the switch from transient to steady state demand still can be seen, it is an absolutely smooth transition.

Further handling tests were performed with this schedule at sea level, which all showed a more than comfortable surge margin of the booster compressor and a proper overall working BBV modulation logic for this condition. Especially the transient response of the BBV demand to the changes of P30V was very satisfactory. The next step was the validation of the P20 dependent components of the logic.

Altitude Testing

The optimized steady state schedule was used as the basis for the further testing, which was performed on the ATF in Pyestock/England. Extensive stability testing was performed under various realistic flight conditions. These flight conditions had been chosen from an analysis of the critical location within the flight envelope concerning the stability of the compressors, i.e. where the minimum surge margin exists. The impact of the BBV on the booster compressor's surge margin had already been regarded in this analysis. So, again, these tests could be used to prove a proper working of the BBV modulation logic.

To clear as much surge margin as possible for the booster compressor, the severeness of the decelerations has been made higher as a standalone measure without overwriting the fuel flow demand as it was done for de-spiking the engine during sea level testing above. The engine control allows for a specific rate of change of the core speed while accelerating or decelerating. This rate of change results from a basic value dependent on corrected HP spool speed multiplied by an altitude (P20V) dependent factor. The latter one is a simple mean to be trimmed, while testing the engine on site. Thus it was used to reach these more severe conditions.

While the engine was tested at an altitude of 40000 feet with Mach 0.4, a rapid deceleration was performed with the nominal setup. Operation of the BBV was absolutely satisfactory.

After scaling the P20 factor up by a factor of 1.5, a rapid deceleration was performed again and suddenly the engine control revealed an offset of more than 11% of fractional BBV area between demanded and actual BBV position (see Fig. 4). Investigations showed, that the rate limiter for opening the bleed valve came into effect during this manoeuvre. It restricted the rate of opening the bleed valve, leading to the actual position not being able to reach the demand. The decision was made NOT to change the opening rate limiter for the following reasons:

- This was the only occurrence of the rate limiter coming into effect seen so far

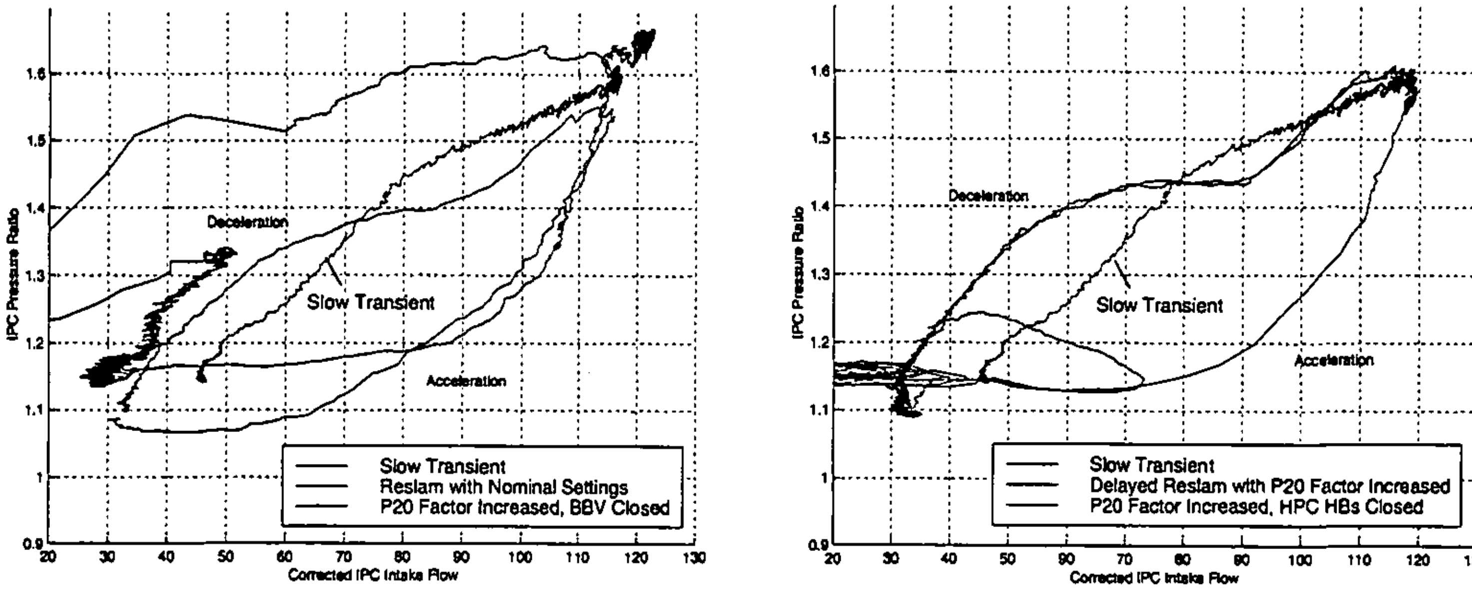

Fig. 5: Manoeuvres at 16500 feet, Mach Number 0.3

- This behaviour was not present during nominal operation at this flight condition, since the nominal P20 factor scales down the engine response at higher altitudes. The BBV has thus enough time to open at altitudes higher than 15000 feet without hitting the rate limiter.
- No instabilities of the booster compressor could be seen even with the rate limiter active.
- The actuator hardware can only support a certain rate of opening the valve, which was used to set the initial value for the limiter.

In order to assess the effect of the BBV on the stability of the compressor, tests have been performed both with the valve operating nominal and the valve trimmed closed. Additionally, the measures discussed above to get a higher booster compressor working line have been used. Two flight conditions have been chosen out of these tests to be included here:

- 16500 feet, Mach Number 0.3
- 40000 feet, Mach Number 0.4

The compressor's behaviour during different manoeuvres at these conditions shall be discussed in the following, proving the necessity of the BBV in principle, but also proving the logic to be working correctly and satisfactory.

Fig. 5 comprises two pictures with the compressor map of the booster compressor in terms of pressure ratio against corrected flow for the 16500 feet altitude condition at Mach number 0.3. Both include the nominal working line, which was achieved for this plot via a very slow deceleration without triggering the transient BBV modulation part. This working line shall serve as the reference working line for the following discussion.

With all control parameters set to nominal, i.e. steady state BBV schedule, VSV schedule, HPC handling bleeds and deceleration P20 factor, an immediate reslam was performed, which means, the throttle for engine control was pushed from maximum power to idle very fast and pushed back to the maximum position, before the engine is able to settle down at idle. The resulting transient working line is shown in the left picture within Fig. 5. The reslam starts at high pressure ratio/mass flow on the right top corner of the compressor map. The transient working line runs down to the lower left corner during the manoeuvre, turns around and rises again to the beginning.

The transient compressor working line for this manoeuvre is mainly influenced by the opening of the booster bleed valve. In the first part of the deceleration, the transient part of the BBV modulation logic demands a very rapid opening of the valve. This leads to a strong drop in the working line, clearly below the reference working line. As already seen on the sea level testbed, this transient demand is reduced, while the rate of change of P30 decreases, the transient working line crosses the reference line at mid power and remains higher than it for the rest of the deceleration. This is the part, where the steady state demand comes into effect.

During the following acceleration, the working line is in principle only influenced by the steady state BBV demand closing the valve, since the main objective of the transient part is surge protection during rapid decelerations. As mentioned, this is reached by a dependency on a falling HPC discharge pressure.

However, in the turnaround point of a reslam, the design is such, that the following increase in P30, which in itself would cause the transient demand to drop rapidly, is put into the transient control with a delay. This avoids rapid closing of the BBV for this case. As mentioned above, the effect of this is the avoidance of working line excursions in the turnaround point, which are clearly not present in the picture above. For this manoeuvre it can be concluded, that the modulation logic reduces the transient working line excursions compared to the reference working line to a minimum for the deceleration. Hence a maximum surge protection for the booster compressor is ensured.

After this nominal manoeuvre, the control parameters have been changed to make conditions more severe for the compressor. The deceleration P20 factor was increased by a factor 1.5 and the BBV was trimmed to remain fully closed. Thus a simulation of an engine without BBV was performed. The resulting working line for a similar reslam as already discussed is also included in the left hand picture.

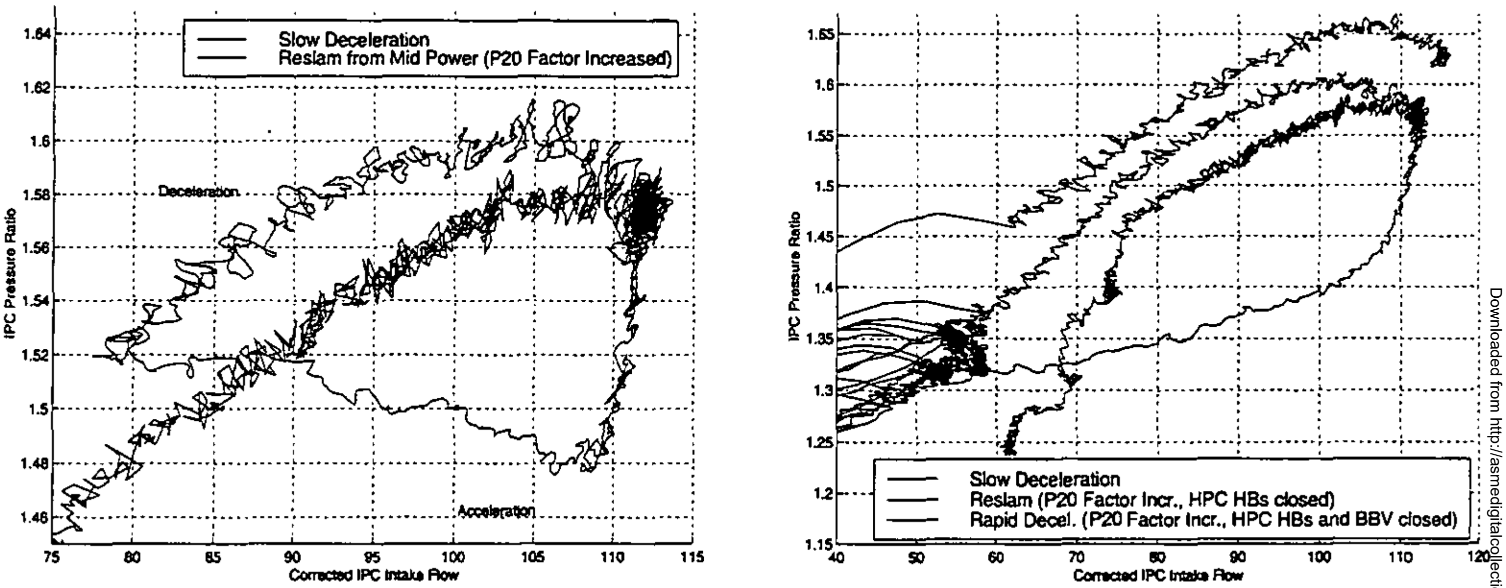

Fig. 6: Manoeuvres at 40000 feet, Mach Number 0.4

The transient working line immediately rises at the begin of the deceleration. A booster induced surge occurs during this manoeuvre, which can be seen in the very strong pressure fluctuations in the picture on the left. Since the engine control of the BR700 family features a surge protection logic to cope with such events, the engine is capable to recover immediately by opening the HPC bleed valves. Also in the low power region, the transient working line is still very high and clearly indicates, how strongly the booster bleed valve is required for surge protection.

On the right hand side in Fig. 5, the impact of a different reslam timing on the transient working line is shown. Beside the reference working line as on the left hand side, this picture includes a rapid deceleration with the HPC handling bleed valves overridden closed as well as a delayed reslam. This means, pushing the throttle back from idle to maximum power is delayed by 60 seconds. The engine is thus allowed to settle down at the low power condition in this scenario. The result is a different thermal constitution of the engine, leading to a probably more severe condition with respect to compressor surge. Both manoeuvres have been performed with nominal BBV schedules and increased acceleration and deceleration P20 factors.

For the deceleration part of both manoeuvres, nearly no difference can be seen in the transient working line. Compared to the left hand picture, the increased P20 factor leads to a stronger deceleration, thus the N2 speed drops more rapidly. Since the transient BBV modulation logic obviously does not react as fast as seen on the left hand side, the working line rises at the beginning of the manoeuvre before falling below the reference working line. But this was not regarded as a reason for changing the transient part of the logic, since the excursion of the transient line is negligible.

The delayed reslam comprised nominal HPC handling bleed settings and is thus able to reaccelerate properly. The difference to the second manoeuvre included is, that two out of the four handling bleeds of the high pressure compressor were trimmed closed. This should lead to a further increase in the booster compressor's working line, thus clearing more surge margin at idle conditions.

Obviously, this trim led to multiple surges in the low power region during the deceleration.

Fig. 6 shows a similar setup as Fig. 5 above. The flight condition was changed to 40000 feet, Mach number 0.4. A slow transient reference working line is included for orientation. Reslams have been performed under this flight condition as well. With all schedules set to nominal and increased acceleration and deceleration P20 factors, the resulting working line is as given in the left hand picture. This reslam was not performed from low power, but from a mid power condition before an HPC handling bleed valve is opened. The working line is constantly above the reference line, but no booster surge was seen. Since the turnaround point also shows no excursions , it could be concluded, that the BBV modulation logic is working properly. While accelerating the engine again, the pressure rise in the booster compressor is done nearly at the end of the mass flow increase, giving a very steep working line towards the end of the manoeuvre.

On the right hand side picture, the whole range of the IPC map for this flight condition is given again containing the reference working line. What clearly can be seen are the opening points of the HPC handling bleeds at corrected IPC massflows of 75 and 68 respectively. The IPC working line drops here in terms of pressure ratio.

With the handling bleeds of the HPC again overridden closed, two further manoeuvres are included in this picture. One reslam with nominal BBV settings and a rapid deceleration with the BBV being additionally closed. In principle, the reslam shows the same behaviour as already discussed in Fig. 5 for the lower altitude condition. The transient working line is constantly above the reference line, but in a very smooth and acceptable manner with respect to surge protection. The switching points of the HPC handling bleeds are not visible anymore during the manoeuvre. Although the rapid deceleration was started from a slightly different power condition, the influence of the additionally closed BBV is obvious. However, the booster is capable under these conditions to decelerate without surge until it reaches low power conditions. Here the effect of the combination of HPC handling bleeds and BBV simultaneously overridden closed leads again to multiple surges.

CONCLUSIONS

The BR715 engine features a handling bleed valve situated after the IPC. A newly developed BBV modulation logic drives this valve according to the steady state and transient needs. The behaviour of the logic in practice had to be investigated during engine testing for certification of the BR715. Mainly the handling and the stability tests performed on both sea level and on altitude test facilities have been used for the validation of the logic in terms of reduction of working line excursions and surge protection. Simulation of transient manoeuvres helped in clarifying special events.

This paper showed up the problems, which have been encountered with the logic and how these problems have been accommodated, if necessary. The steady state schedule for the logic had to be reworked due to the combination of the steady state and the transient logic part during rapid decelerations. Other occurrences like rate limiters limiting the opening of the valve and working line excursions due to the transient modulation not being fast enough have been regarded as negligible and having no negative effect neither on the stability of the compressor nor on the BBV actuator hardware.

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