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CLEAN – Bench Adaptation and Test for a Complex Demo Engine Concept at ILA Stuttgart

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ABSTRACT

Within the 5th EU Framework Programme a technology platform called EEFAE (Efficient and Environmentally Friendly Aero-Engine) is funded by the EC. One part of the technology platform consists of the CLEAN programme (Component VaLidator for Environmentally–friendly AEro-ENgine) that aims for long term application of new technologies in aero engines [1, 2, 3]. The five major partners in the CLEAN programme are Snecma Moteurs, Avio, Volvo Aero Corporation, Eldim and MTU Aero Engines.

The paper deals with the realisation of the different subsystems and control systems to adapt the bench for the complex test of the vehicle and the test campaign itself.

The testing of the vehicle takes place at the altitude test facility (ATF) at the University of Stuttgart in strong corporation with the Institut für Luftfahrtantriebe (ILA). The main components of the test vehicle are a high pressure core, a high-speed low pressure turbine and a heat exchanger in the exhaust gas zone. Since the vehicle is a component validator and will not include a low pressure compressor, a gearbox and a closed oil and air system a lot of effort has to be put into the provision of subsystems and control systems to perform the test.

Several questions had to be solved during the concept and design phase. How to handle the power of up to 23 MW released by the low pressure turbine? How to supply the components of the vehicle with air and oil with engine-like conditions? How to survey all the subsystems and avoid long lasting interruptions due to the complexity of the overall system?

NOMENCLATURE

Symbols

p_0 [kPa]	pressure in front of vehicle
p_9 [kPa]	pressure behind throttle of vehicle
T_0 [K]	temperature in front of vehicle
$\dot{m}_{25}$ [kg/s]	mass flow through the vehicle

Abbreviations

ATF	Altitude Test Facility
BMC	Bench Master Controller
CAP	Surge Avoidance System
CLEAN	Component Validator for Environmentally-friendly Aero-Engine
CS	Control System
CRT	Compressor Run Time
CTTC	CLEAN Technical Test Committee
EC	Exhaust Casing
HEX	Heat Exchanger
HP/LP	High/Low-Pressure
ILA	Institut für Luftfahrtantriebe
LPC	Low-Pressure Compressor
LPT	Low-Pressure Turbine
MMI	Man-machine Interface
PL	Power Lever
PULS	Data Acquisition Software Package
SAS	Secondary Air System
SQF	Squeeze Film
TMEA	Transportable Data Acquisition System
VSV	Variable Stator Vanes
WCOC	Water cooled Oil Cooler
WDT	Watchdog Timer

INTRODUCTION

A complete Aero Engine usually is setup with all the necessary equipment and ancillaries directly at the engine to run autonomously by supplying the engine with fuel and giving control commands to the vehicle control system.

The technology demonstrator CLEAN in the 5th EU framework programme consists of a HP core, a high-speed LPT and a heat exchanger (see Fig. 1). Details on the concept of the CLEAN vehicle have been handled in [1]. Due to missing LPC, water brakes have to be used for the LPT power consumption. Since this demonstrator "Vehicle" does not have a gearbox, closed oil or secondary air systems, it poses a substantial demand for a complex control for several sub systems and an overall test support.

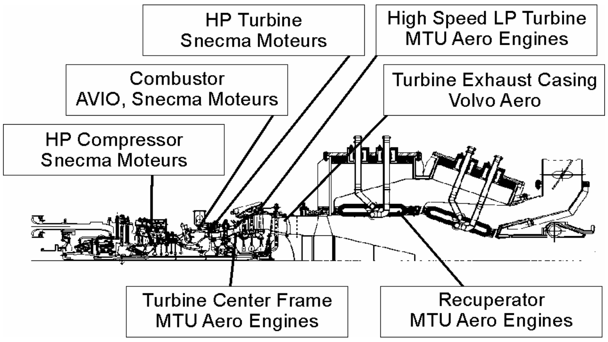


Fig. 1: CLEAN engine general arrangement

BENCH ARRANGEMENT AND ADAPTATION

To achieve a setup of the test bed that completely fulfills all the needs for the complex CLEAN test, several iterations have been done before the realisation of the test. Therefore, the concept phase for the bench arrangement and adaptation has been started mid of 2002.

The vehicle has to be supplied with an air mass flow of up to $\dot{m}_{25}$ = 45 kg/s air in the main path (p_0 = 100 to 330 kPa, T_0 = 273 to 400K, $p_9 < 15$ kPa) and additionally a secondary air supply for the vehicle, the heat exchanger and some cooling air for instrumentation in sum of up to 8 kg/s (max. 1600 kPa, 820K). The bleed air of up to 5 kg/s at high temperature has to be exhausted.

Several Bearings and squeeze films inside the vehicle have to be supplied externally with oil for lubrication and cooling.

The LPT produces a maximum power of 23 MW at a rotational speed of 8300 rpm that due to the missing LPC have to be handled by the bench.

Since the combustor is designed with a two-stage burner two complete independent fuel circuits have to be taken into account.

The vehicle produces approximately 200 kW of thermal power to the environment that due to the missing fan and the setup in a closed test bed have to be handled by the bench system.

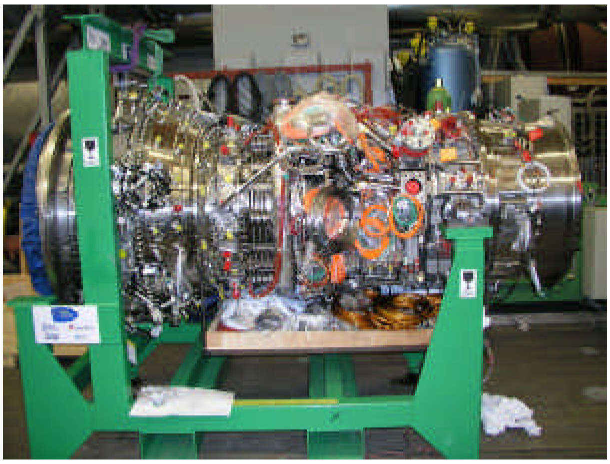


Fig. 2: CLEAN Test Vehicle

Due to the sensitivity of the equipment around the test vehicle a temperature of 50 °C in a distance of 1 m to the vehicle should not be exceeded.

There are two test areas at the ATF of ILA Stuttgart to test engines and rigs. The test bed 1 normally used for engine testing is realized as a closed test cell (length 11 m, Ø 3,6 m) with a side opening door and is followed by a large exhaust gas cooler. The test bed 2 normally used for cold rig testing is nearby and in parallel to test bed 1 (see Fig. 3).

Both test beds can be supplied with air by up to five compressors in different configurations for feeding, suction and mixed operation.

In an early phase of the programme both possibilities to use test bed 1 or 2 have been investigated. The decision has been taken to use test bed 1 because the path of the air flow through the vehicle is in line with the test bed and the hot exhaust gas can directly be fed to the exhaust gas cooler. At test bed 2 the exhaust flow has to be redirected by 180° to path the hot exhaust gas to the cooler which leads to high pressure losses and extended costs, although the accessibility to the vehicle would be much better than in the test cell of test bed 1.

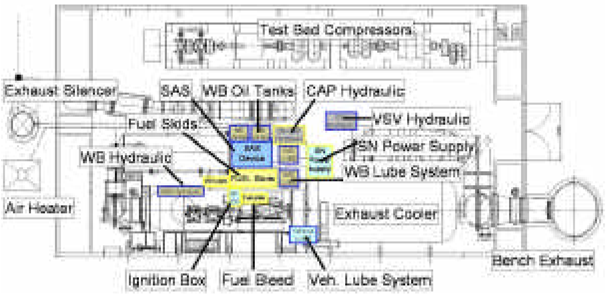


Fig. 3: Layout of the test bed and location of the bench systems

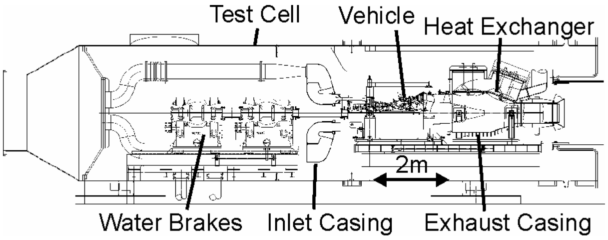


Fig. 4: Test Cell Configuration

Fig. 4 shows the chosen configuration with a water brake system in front of the vehicle, the vehicle itself and the exhaust casing with the heat exchanger in the region of the opening of the test cell. For the CLEAN tests the side-door stays open to allow all supply and instrumentation lines to be configured, therefore, the gas path has to be closed to the ambient. To feed the HPC the inlet air flow has to be routed through four equally spaced pipes from the front of the test cell to the inlet casing. The inlet casing has been equipped with inserts to ensure a uniform and straightened flow to the HPC. The design of the inlet casing has been validated by numerical calculations of the flow distribution.

For the secondary air 14 circuits have to be supplied with air at different pressures and temperatures. Some of the circuits have to be controlled in pressure and temperature or mass flow in dependency of the overall mass flow $\dot{m}_{25}$ to achieve an engine-like behaviour of the vehicle.

The secondary air system has been realized with the following components. Two compressors deliver the air for the whole system at two pressure levels. One already existing compressor at ILA for general purposes delivers 3kg/s at 800 kPa and a maximum temperature of 310 K, a second one has been setup especially for this programme to deliver air at a mass flow of up to 5 kg/s at a high pressure level of 2000 kPa.

Fig. 5: Installation of the Secondary Air System (SAS) valve bay in front of the test cell

To allow arbitrary temperatures of 310 K up to 820 K in different circuits the high pressure air is separated in two parts, one of the flows is routed over an air heater powered by heating oil to deliver hot air.

At the valve bay in front of the test cell all supplies are collected and lead to the mixing valves for the different supply circuits (see Fig. 5). To ensure continuous conditions for each supply line independent of the changes in other circuits all the excessive amount of air is exhausted over a chimney controlled by separate valves.

The oil system has to supply all of the five vehicle bearings and the corresponding squeeze films. To achieve a good backflow of the oil to the oil system the system has been located in the cellar below the test room. Two main pumps generate the oil flow for all circuits, the pump speed depends on the HP core speed to achieve engine-like conditions.

In case of a failure of the subsystem 90 s of emergency supply for the bearings have to be ensured to run down the vehicle safely which has been realized by switching a third oil pump from the back flow tank directly onto the two supply lines.

A tandem water brake configuration of two existing water brakes has been chosen to handle the power of the LPT. Each of the water brakes (Froude Consine HS690, HS790) has been equipped with its own oil and hydraulic supply system. In case of a loss of power or damage of the supply system a passive emergency oil supply system has been setup which is capable to drive the water brake system until the vehicle has been safely shutdown.

Fig. 6: Water Brake System installed in the Test Cell

Both water brakes are controlled by one control system to achieve a well-balanced load on the water brakes. The water brakes have been supplied with cooling water by an existing water cooling circuit at ILA, the necessary water flow for both water brakes is 16 m³/min.

The external cooling of the vehicle has been realized with a double fan unit that enables to blow up to 60000 m³/h air from the ambient of the test building over large pipes into a test cell opening above the front water brake. The cooling air is guided by metal plates around the inlet casing to the vehicle casing.

Two fuel skids have been delivered by Snecma Moteurs which have been mounted in front of the test cell to drive the two stages of the combustor. Additionally a special valve setup has to be installed to give the possibility to purge the fuel lines directly at the vehicle to avoid coking of the injectors.

Several additional smaller subsystems as the ignition box, auxiliary hydraulic systems for the variable stator vanes (VSV) or the surge avoidance system (CAP) had to be considered in the bench configuration.

Installation of the bench subsystems has been started end of May 2004. The installation of the vehicle has been done in August 2004. In parallel all the subsystems including the measurement equipment have to proven by acceptance tests during August 2004. The installation has been completed for testing mid of September 2004. (see Fig. 7).

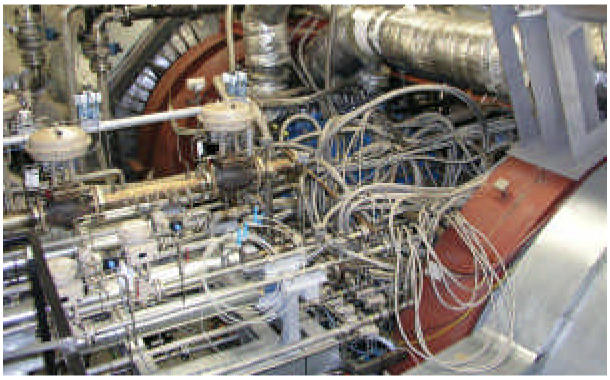


Fig. 7: View on the test cell opening after installation of the CLEAN vehicle with all supply lines

CONTROL SYSTEMS ARCHITECTURE

The whole Control System (CS) structure has been realised as an integrated decentralised control structure, as shown in Fig. 8.

The Clean CS consists of two hierarchical levels of authority: dedicated CS and the Bench Master Controller (BMC).

Dedicated CS provide control and safety for their particular subsystem, thus, a local and decentralised "intelligence" has been achieved. These controllers have their own sensors and actuators to fulfill their tasks. Dedicated CS must ensure their own state and health, and provide these data to the BMC. They are also able to react according to BMC command signals.

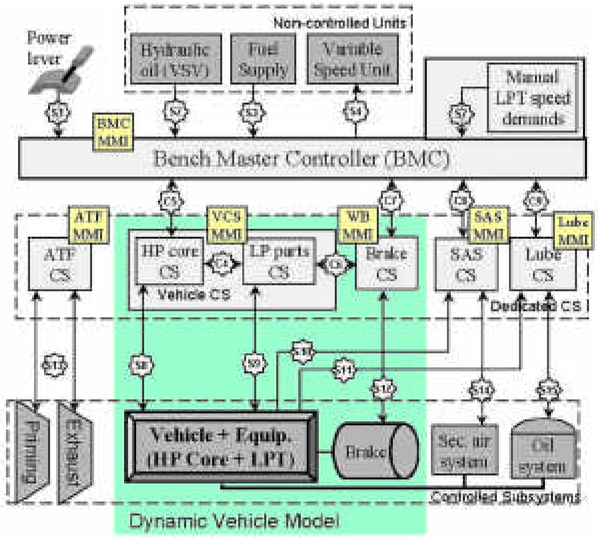


Fig. 8: General CS structure

There is no any direct communication between subsystem controllers and all communication goes over the BMC. Logically, the water brake CS belongs to the Vehicle CS since it controls the LPT speed. Hence, direct communication between the Vehicle CS and Brake CS has been established. Every controller has its own MMI to provide monitoring and adjustments within the scope of its subsystem and controller.

The BMC provides an overall test supervision by using the state and health signals from dedicated CS, by sending demands for recovery actions, by supervising the control fluid supplies. It also provides the PL management, controls the change of test phases, and provides redundancy for Vehicle CS critical functions since all CLEAN CS are single-lane controllers.

Dedicated CS

ATF CS is a facility of ILA Stuttgart. It controls the priming pressure and temperature at the HP core inlet, and suction pressure at the vehicle exhaust.

Vehicle CS includes the HP core controller from Snecma Moteurs and the LP scheduler from MTU Aero Engines. It runs on a dSpace platform with control cycle of 20ms.

The HP core part controls the fuel flow for the low-NOx two-stage combustor and the HPC VSV positions. It also reacts on the signals from another dedicated fast-processor platform for active surge control.

The LP part provides the LPT speed demand scheduling, either in automatic mode, following the HP core speed dependent demand, or in manual mode, generating a separate demand for LPT mechanical or aerodynamic speed. It also provides over-speed and shaft shear protection algorithms.

The water brake CS belongs logically to the vehicle controller since it actually controls the LPT speed over the speed control of two water brakes in tandem arrangement. This controller is a product of the water brake provider, Froude Consine.

The operational limits of the brakes connected in tandem are 25 MW, 43 kNm and 10000 rpm. The power absorbed by the dynamometer is dependent upon the mass and the velocity of the water circulating. Two valves control the water flow: inlet valve open-loop control provides optimum running and control conditions, while the outlet valve is a fast-response closed-loop controlled over a wide range of speed and power.

The SAS CS has to control cooling and sealing air for the HP core and the LPT from an independent air source to reach the same vehicle behaviour as in the full engine. There are two pressure and one mass flow controlled circuits with source of 800 kPa, and also three mixed pressure/temperature and one flow/temperature controlled circuits with source of 2000 kPa, as shown in Fig. 9. These control circuits need also vehicle signals to provide engine-like responses.

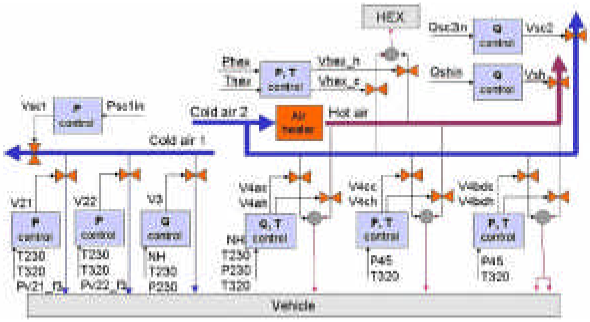


Fig. 9: SAS control circuits

There are also additional valves adjustable only via SAS MMI or closed/opened automatically during recovery actions.

The SAS CS is a Siemens Simatic S7 based controller with the PC workstations as the SAS MMI for monitoring and adjustments of SAS parameters.

The Lube CS controls the oil flow in five bearings, oil pressure for their squeeze films, and the water cooled oil cooler (WCOC). To achieve an engine-like behaviour, the oil flow control law is a function of the core speed. Lube CS also provides safety reactions in case of supply pumps failure. It is also a Siemens Simatic S7 based controller.

Bench Master Controller

The BMC is a high-level bench controller to provide an integrated and co-ordinated vehicle test support. The functionality of BMC includes:

- Handling of Power Lever (PL) demands for HP core and LP spool speeds (e.g. pilot vs. software PL, mechanical vs. aerodynamic speed).
- Control of test phases.
- Supervision of dedicated controllers via activity of serial/optical links and Watch Dog Timers (WDT).
- Release of recovery actions.
- Redundancy for LPT over-speed and shaft shear detection.
- Detection of LPT shaft torsion vibrations.

- Recording functions (trend, event/manually triggered).
- Time stamping provision.

A special attention must be given to the control of test phases, as given in Fig. 10. For the phase transitions marked with B, the BMC decides if the more critical phase can be entered or not. For this, special conditions must be met and the operator must confirm the phase transition. Other transitions can take place any time depending on safety actions and PL movements. Since some safety actions within dedicated CS are phase dependent, the BMC must also send the phase information to those CS.

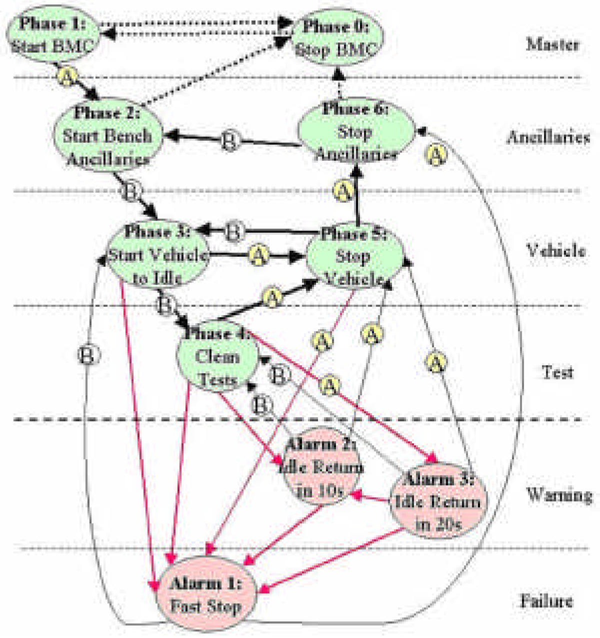


Fig. 10: Test phase definition

Controller Integration

Since the dedicated CS have full authority over the controlled subsystems, the controller communication and integration is mainly determined by safety requirements. The vehicle safety requirements are result of the failure modes and effects analysis (FMEA) for the vehicle components (HP core, LPT, HEX and EC). These requirements are then distributed to dedicated controllers when they already have the required instrumentation on disposal. Therefore, the BMC received safety requirements for all non-controlled units, e.g. supervision of fuel and hydraulic oil supply.

The communication between controllers is shown in Fig. 11. A high-speed optical link (1 Gb/s) connects the BMC with the vehicle CS. It provides co-ordination of control modes, PL signal, test phase, time stamping, and safety signals. The BMC has a direct connection to cut the fuel in case of an emergency shutdown.

The communication to SAS CS, Lube CS and brake CS uses hardwired safety signals and a serial link due to different and slower controller platforms for subsystems.

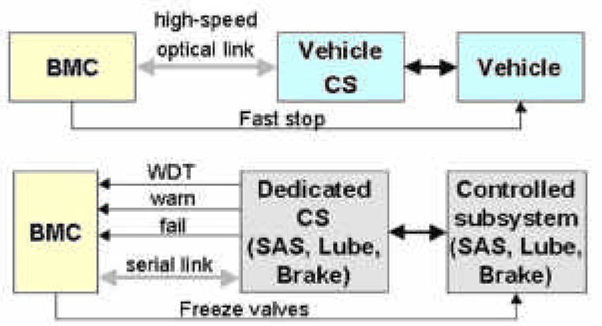
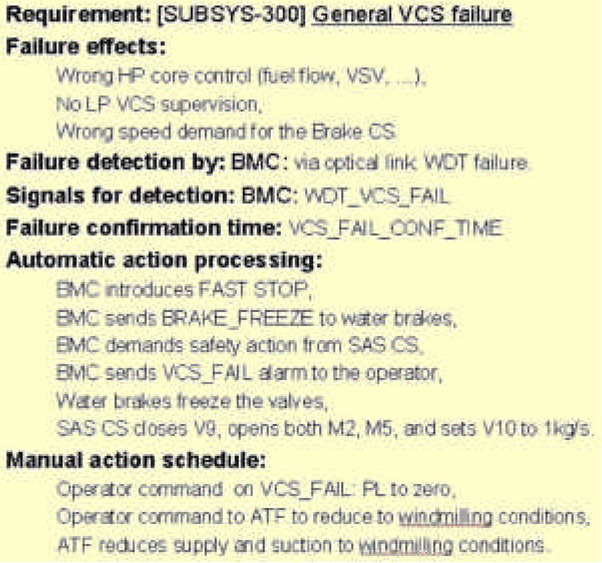


Fig. 11: Controller communication

A special analysis for co-ordinated controller reactions had to be done in case of general subsystem failures. An example requirement for the general vehicle CS failure is given in Fig. 12. For a subsystem failure the failure effects must be clear and also which controller can recognise the failure.



Requirement: [SUBSYS-300] General VCS failure

Failure effects:

Wrong HP core control (fuel flow, VSV, ...),
No LP VCS supervision,
Wrong speed demand for the Brake CS

Failure detection by: BMC: via optical link WDT failure

Signals for detection: BMC: WDT_VCS_FAIL

Failure confirmation time: VCS_FAIL_CONF_TIME

Automatic action processing:

BMC introduces FAST STOP,
BMC sends BRAKE_FREEZE to water brakes,
BMC demands safety action from SAS CS,
BMC sends VCS_FAIL alarm to the operator,
Water brakes freeze the valves,
SAS CS closes V9, opens both M2, M5, and sets V10 to 1kg/s.

Manual action schedule:

Operator command on VCS_FAIL: PL to zero,
Operator command to ATF to reduce to windmilling conditions,
ATF reduces supply and suction to windmilling conditions.

Fig. 12: Requirement for vehicle CS failure

Timely critical actions must be given to controllers and the controller design must be flexible to assure provision of co-ordinated actions. For general controller failures it is important that the BMC can freeze the subsystem behaviour to protect against wrong actuator positioning. An automatic message has to be provided to the test operator that predefined manual actions can be introduced.

CLEAN TEST CAMPAIGN

The CLEAN test campaign has been started end of September 2004. Before the test a lot of organizational work has to be done to ensure that all partners have the same understanding how the testing should be performed to fulfill the CLEAN objectives.

Testing at ILA usually is restricted to four evenings a week, a test evening can begin at 05:00 pm and last up to 12:00 pm. Due to the enormous power consumption of the bench systems a testing at daytime is too expensive.

For the testing an organizational structure has been defined to clarify the responsibilities of every participant of the test (see Fig. 13).

Central point of the testing team is the test engineer in command who is responsible for the testing on site.

He defines in cooperation with the partner companies engineers the daily test programme in the afternoon of every test day. CTTC or higher authorities can influence the test programme before the start of the test evening, after test start a change of the test programme is not allowed to avoid confusion during the test which could lead to expensive additional test time.

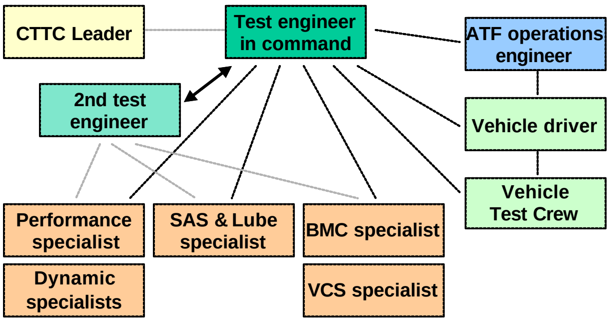


Fig. 13: Test organization chart

The test engineer in command directly communicates with the ATF operations engineer, the 2nd test engineer who has an advisory function and can support the test engineer in command in case of trouble, the vehicle driver and the vehicle test crew. The specialists for the different control and measurement systems can give warnings to the test engineer in command via headset communication.

The CLEAN vehicle and bench have been equipped with an amount of over 1600 measurement lines to ensure safe operation and to generate the data pool that is necessary for the validation of the proper design of all vehicle components.

Instrumentation Type	Vehicle	Bench
Air Pressure	533	11
Differential Pressure	21	0
Fluid Pressure	14	10
Dynamic Pressure	54	0
Gas Temperature	632	7
Fluid Temperature	19	20
Strain Gauges	175	3
Clearancometer	40	0
Speed Sensors	10	2
Vibration Sensors	31	0
Massflow	0	17
Others	0	5
Overall	**1529**	**75**

Fig. 14: Instrumentation overview

Different measurement systems have been setup at the ILA bench to allow the recording of all the parameters. The steady state measurement system that is available as a standard system at the ATF of ILA Stuttgart has a capability of 768 pressures and 540 temperatures with a sample rate of 4 Hz. Data configuration and recording has been done with the software package PULS that has been developed by MTU.

For transient measurements a mobile data acquisition (TMEA) has been used that can record up to 550 channels with 20 Hz.

Due to the need to record over 240 dynamic channels the both major partners for the test MTU and SM had to bring along their own dynamic systems.

All measurement systems have been installed, configured and tested in August and September 2004 just before the test starts.

Due to the high costs that have to be taken into account for the operation of the test bed an effective and optimized test programme has been investigated (see Fig. 15).

The first five test points have been planned to validate the function of all bench systems in cooperation with the vehicle and evaluate the basic performance of the vehicle components.

The next test objective is to validate the low NOx emissions of the two-stage combustion chamber. A special gas measurement truck has been setup at the ATF to measure the ICAO parameters of the combustor.

LPT characterization is performed with the next two test points.

One objective is to validate the TEC and its capability to withstand temperature up to 1000 K. This test point is similar to some test points necessary for the heat exchanger verification, therefore, it has been integrated in the heat exchanger testing.

The heat exchanger has to be tested in two different positions named Pos A and B.

In advance to surge avoidance tests of the HP core basic transient tests have to be performed to understand the transient behaviour of the vehicle.

For the surge avoidance testing the influence of variable stator vanes and bleed valves have to be investigated.

Test objectives	Test description
1	Windmilling - Dry cranks
2	Windmilling - Wet cranks
3	Start to Idle
4a	Ambient Break-In
4b	Feeding Break-In
5	LPT Break-In / Core Characterization
6	NOX_ICAO
7	LPT Mapping
9	LPT Reynolds
8, 10	HEX 1 (Pos B) / TEC 1000 K Test
10	HEX 2 (Pos A)
11	Basic Transient Tests
12	CAP validation : VSV & Bleed effects
13	CAP validation : Surge avoidance

Fig. 15: CLEAN test programme

The test campaign has been started on 26th of September 2004. The first tests have been performed successfully, with some adaptations of parameters of the vehicle control system to the real vehicle behaviour. All systems worked as expected with only minor problems, e.g. onset of vibrations at the combustor during the feeding break-in at higher pressures. In order to allow a save vehicle operation for all planned test runs the test sequence has been adapted to actual bench and engine conditions. Additionally some slightly changes of core parameter settings were necessary due to new results of high pressure combustor tests running in parallel at CEPr in France.

After a period of ten weeks and a system run time of 82 hours the CLEAN test campaign has been successfully completed on 10th of December 2004.

Results of CLEAN components will be presented in a parallel published paper [4].

Fig. 16: Control room during testing

SUMMARY

All bench subsystems have been setup in time and worked as expected. The concept of dedicated controllers has been proven with its capability to optimally support this kind of complex test setup.

The tests at the ATF at ILA in Stuttgart have been completed successfully without any damage to the CLEAN vehicle in December 2004 after a test period of ten weeks.

All planned tests of programme partners have been performed and the CLEAN objectives defined in the EU contract have been fulfilled.

It has been demonstrated within the CLEAN programme that the fruitful cooperation between the different European aero engine companies gives important impulses for the development of next generation aero engines.

ACKNOWLEDGEMENTS

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