DOI: 10.13009/EUCASS2019-690

Flight Instrumentation for the Reusability Flight Experiment ReFEx

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Abstract

The German Aerospace Center (DLR) is preparing the sub-scale reusability flight experiment ReFEx planned to be launched in 2022 using a Brazilian VSB-30 sounding rocket. Main goal is the demonstration of a controlled autonomous re-entry flight from the hypersonic flight regime down to subsonic velocities and to test key technologies for future reusable first stages.

The vehicle contains an extensive flight instrumentation consisting of pressure, temperature, heat flux and acceleration sensors and a corresponding data acquisition system. This paper presents an overview of the planned flight instrumentation for the ReFEx vehicle.

1. Introduction

After several decades of using expendable launch vehicles for access to space reusability is getting more and more important in the space transportation sector. Since the first stage represents the largest investment in a multi-stage launch vehicle it is the most interesting vehicle component concerning reusability. One approach to return the first stage to its launch site or other landing sites is the application of winged configurations. This has the advantage that after successful burn-out of the first stage most of the energy can be dissipated by aerodynamic means during re-entry, and therefore only a small amount of additional propellant is necessary compared to first stages without wings and a purely propulsive return. In order for this advantage to take effect it is important that the weight of wings and necessary additional components (e.g. control surfaces) is smaller than the weight of fuel which would be used during a propulsive return flight. On the other hand a disadvantage of winged first stage configurations is their susceptibility to atmospheric conditions (e.g. winds) due to the larger effective aerodynamic area. Therefore an autonomous flight control system capable to adapt to the specific conditions during flight from high supersonic Mach numbers down to the subsonic regime is essential for these systems.

While a lot of activities concerning reusability are carried out by US companies like SpaceX and Blue Origin, several aerospace agencies including DLR are also conducting research in the field of Reusable Launch Vehicles (RLV). Former DLR re-entry flight experiments like SHEFEX I & II were focused on TPS (Thermal Protection System) technologies using sharp-edged configurations for re-entries with higher Mach numbers above Ma=6 [1], [2], [3]. In comparison to SHEFEX-I which performed an uncontrolled re-entry, SHEFEX-II also included four small control surfaces (canards) for active flight control during re-entry [4].

Compared to SHEFEX-I & II the ReFEx vehicle is a winged configuration with several control surfaces representing a winged first stage of a reusable launch vehicle. The re-entry configuration (see Figure 2) has a length of 2.7 metres, a wing span of about 1 metre and a mass of 400 kg. ReFEx will be launched on a VSB-30 sounding rocket and will reach altitudes and velocities similar to a first staging event. Afterwards it will perform a return flight along a trajectory comparable to a returning winged first stage RLV. Several key technologies are demonstrated / tested within the ReFEx project including aerodynamic design of a vehicle which is capable of a stable flight through many flow regimes (from supersonic to subsonic), guidance, navigation and control for on-board trajectory optimization during flight and health monitoring of the vehicle using extensive flight instrumentation and advanced sensors [5], [6].

The flight instrumentation consists of different kinds of sensors to measure pressure, temperature and heat flux on the vehicle outer surface. Several temperature sensors to monitor the temperatures of internal components, internal vehicle structure and wing leading edges are also included in the flight instrumentation. Some of the internal

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temperature measurements are conducted via fibre optic sensors based on a fibre Bragg grating method. Some pressure sensors at the nose are used to form a Flush Airdata Sensing (FADS) system. Using a dedicated software algorithm and the measured pressure data it is possible to determine angle of attack, angle of sideslip, static pressure of the free-stream and impact pressure.

All acquired sensor data are sent to the ground station via telemetry and at the same time are stored on-board with a higher sampling frequency on corresponding memory units. As ReFEx does not contain a parachute system, the memory units are designed to be crash resistant. In addition to the sensors four optical cameras, two at the front and two at the back end of the vehicle, are used to record high-definition videos of the complete flight. These are also stored on crash resistant memory units. Beside temperature sensors which measure the temperature at discrete locations on the ReFEx vehicle, two infrared cameras are used to get two dimensional temperature distributions of the upper sides of the front control surfaces. Several different electronic boxes are used for flight instrumentation sensors, video cameras and infrared cameras which perform functions like sensor signal conditioning, amplification, analog-to-digital conversion or camera control.

This paper presents an overview of the different parts of the ReFEx flight instrumentation after a successfully performed preliminary design review (PDR).

2. ReFEx Flight Instrumentation

The flight instrumentation consists of the following main units which are described in detail in the following sections:

- Two electronic boxes for sensor data acquisition including their memory units, see section 2.2.
- Fibre optic sensing (FOS) electronic box including its memory unit, see section 2.3.
- Four optical camera assemblies including their corresponding electronic boxes, see section 2.4.
- Two infrared camera assemblies including their corresponding electronic boxes, see section 2.5.
- Ten breakout-boxes (BOBs) for interconnection between sensors and electronic boxes, see section 2.6.

Table 1 shows a summary of the planned flight instrumentation sensors. Overall 131 sensors are acquired by the two electronic boxes which perform signal conditioning, amplification and analogue-to-digital conversion for the analogue sensor signals. Most sensors are mounted to the outer surface of the vehicle except for the PT100 sensors and some thermocouples which are used for internal temperature measurements of boxes and structure.

Table 1: ReFEx flight instrumentation sensor overview (PDR status)

Sensor type	Quantity	Remark
Pressure sensors	30	Absolute or differential
Thermocouples	36	Type K thermocouples
PT100 temperature sensors	32	Internal temperature measurements
Heat flux sensors	12	Total heat flux
Coaxial-thermocouples	18	Type E thermocouples
Accelerometers	3	3-Axis accelerometer

2.1 Flight Instrumentation Layout

Figure 1 shows the layout of the flight instrumentation. The two main data acquisition units (EBX 1 and EBX 2) for sensor data acquisition are connected to their corresponding memory units and to the ReFEx power distribution unit (PDU) providing a nominal voltage of 28 V. In addition each EBX is connected to the ReFEx data handling system (DHS) via a digital serial RS422 line for sensor data transmission. The DHS is responsible for transmitting the sensor data to the ground station via telemetry. EBX 1 is furthermore connected to the hybrid navigation system (HNS) via a separate RS422 line for transmission of the FADS data which include angle of attack and sideslip, impact pressure and static pressure. Although the HNS also determines these parameters using a combination of signals from gyroscopes, accelerometers and a GPS receiver, values provided by the FADS system are used as a second source of information. In contrast to HNS, values calculated by the FADS system also include actual wind conditions at the vehicle location which is especially important at lower flight speed in the sub- and transonic regime.

The FADS pressure sensor data acquisition and the execution of the corresponding software algorithm are conducted by one of the circuit boards of EBX 1 which is only used for this purpose and does not acquire any other sensors.
EBX 1 and EBX 2 also contain a further serial interface to acquire a navigation message from the HNS via a digital RS485 line. This message contains among other parameters the exact system time which is used for all on-board systems. The message is included in the sensor data stream sent to the DHS for time synchronisation in the post-flight analyses.
All flight instrumentation sensors are connected to electronic boxes via several breakout-boxes (BOB). Each sensor is equipped with a separate connector and breakout-boxes are used for the interconnection between these individual connectors and a 37-pin D-Sub connector which is attached to the EBX.
In addition to the aforementioned navigation message containing the system time a pulse-per-second (PPS) signal from the HNS is routed to each EBX via a breakout-box. These signals are recorded by one of the sensor acquisition channels and can also be used for time synchronisation during the post-flight analyses.

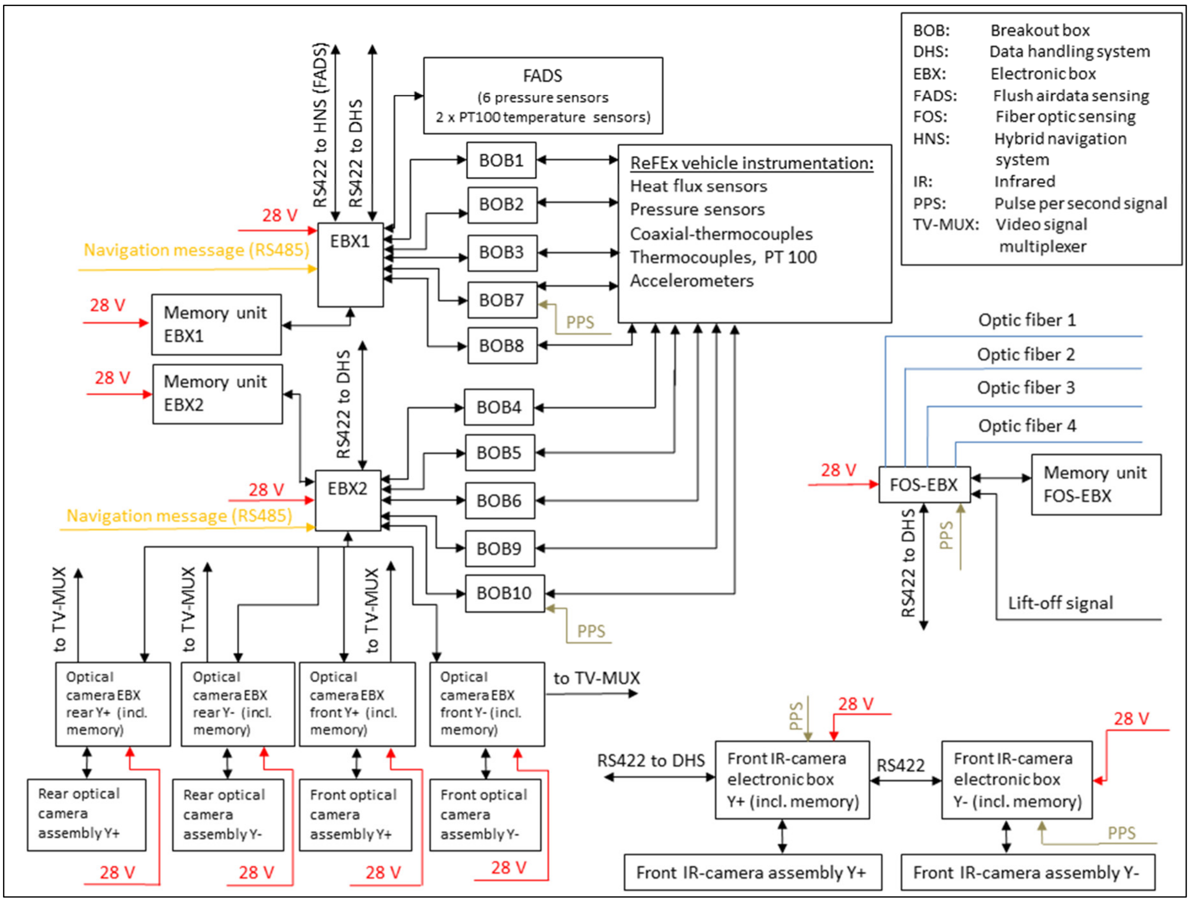

Figure 1: Block diagram of the ReFEx flight instrumentation

The fibre optic sensing (FOS) system is autonomous and not connected to EBX 1 or EBX 2. The main unit is the FOS electronic box (FOS-EBX) to which four optic fibres are attached. Each fibre can contain up to six temperature measurement locations along the fibre. The FOS electronic box is powered by a separate channel of the ReFEx PDU (28 V). Performed temperature measurements are transmitted to ReFEx DHS via a serial RS422 line and in addition are stored on a separate memory unit. Because the FOS electronic box does not contain a RS485 interface for the navigation message, a pulse-per-second signal from HNS is routed to the FOS-EBX and included in the data stream for later time synchronisation. A dedicated lift-off signal (from HNS) is used as an indicator to start the measurements.
The flight instrumentation contains four optical cameras, two at the vehicle rear end and two at the front end directly behind the canards, see Figure 2. These optical cameras are separated into lens modules which are integrated into small camera fins for optical access (optical camera assemblies) and electronic boards integrated into the camera electronic boxes. Each board contains a memory card for high-definition (HD) video data. The memory cards are retrieved after vehicle recovery. In addition each camera sends an analogue video signal in PAL-format to a separate channel of the ReFEx TV multiplexer (TV-MUX). The vehicle contains two video transmitters so two video signals

DOI: 10.13009/EUCASS2019-690

can be transmitted simultaneously. All optical camera electronic boxes also have a connection to the same circuit board of EBX 2 which is used for camera control.
Two infrared (IR) cameras are used to monitor the temperature distribution of the upper sides of the front control surfaces, see Figure 2. The actual infrared cameras are integrated into small fins with infrared-transparent windows. The corresponding electronics including memory cards are integrated into separate electronic boxes which are interconnected via a serial RS422 line. One electronic box is also connected to the ReFEx DHS for data transmission. Due to the limited bandwidth only part of the infrared data are sent to ground via telemetry, but all recorded infrared data are stored internally on the corresponding memory card. Each box also acquires a PPS-signal from the HNS for later time synchronisation because the electronic boxes do not contain RS485 serial interfaces for the navigation message. The following figure shows the locations of optical and infrared cameras on the ReFEx vehicle.

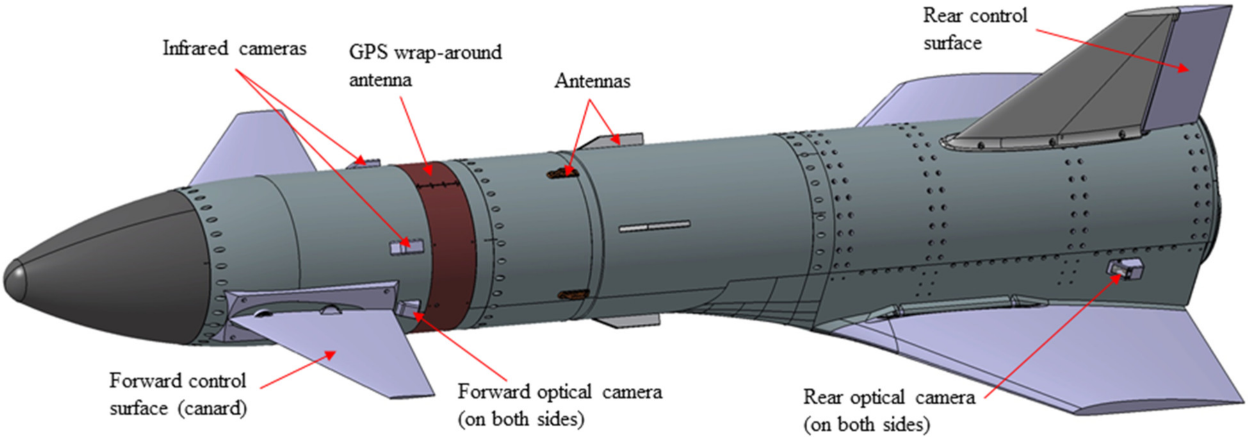

Figure 2: Optical and infrared camera positions on ReFEx vehicle (re-entry configuration)

2.2 Electronic Boxes for Sensor Data Acquisition

Figure 3 shows a three-dimensional view of EBX 1. Both electronic boxes consist of seven circuit boards stacked on top of each other. Each board with dimensions of 100 x 80 mm is integrated into an aluminium frame. The circuit boards for sensor acquisition are equipped with a 37-pin D-Sub connector. The topmost boards of the boxes are equipped with a 9-pin D-Sub connector for power supply and a 15-pin D-Sub connector for a connection to the ReFEx DHS and the corresponding memory unit.

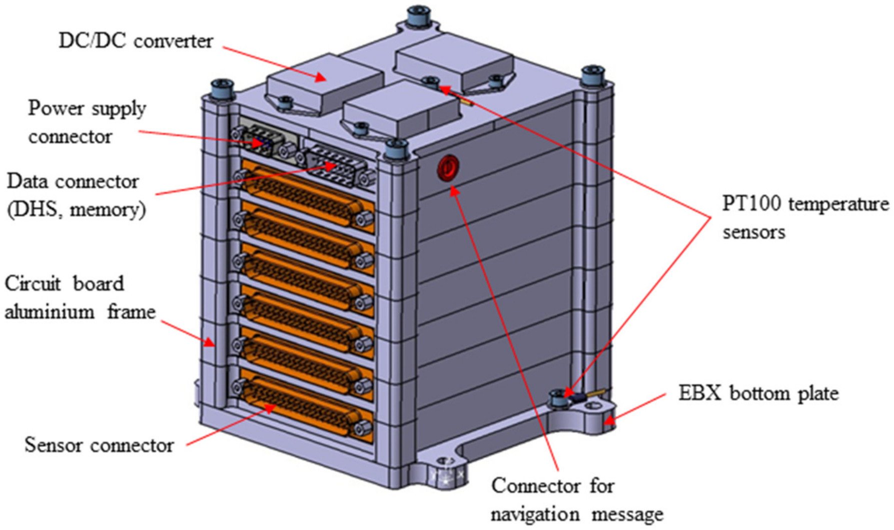

Figure 3: Electronic box EBX 1 (dimensions 122 x 134 x 140 mm)

A third connector (4-pin LEMO) on the topmost frame is located at the side (the round red connector in Figure 3) and is used for connection to the ReFEx HNS (navigation message). For EBX 1 the lowermost circuit board is used

DOI: 10.13009/EUCASS2019-690

for acquisition of the FADS pressure sensors and the execution of the FADS algorithm software. A 9-pin D-Sub connector at the back side of the aluminium frame is used for the connection to the ReFEx HNS (FADS data). All circuit board frames are fixed to the aluminium bottom plate with four M5 screws at the corners of the frames. The fixation of the EBX to the ReFEx structure is done by four M6 screws attached to the bottom plate. To convert the system voltage of 28 V to the necessary voltages for EBX and sensors, several DC/DC-converters are used which are located on the top plate. Each circuit board for sensor acquisition can acquire up to 18 passive sensors (e.g. thermocouples) with a sampling frequency of 1 KHz. If active sensors like pressure sensors are attached, the maximum sensor number reduces because some pins of the connector have to be used for the sensor power supply. For example nine pressure sensors, each with a separate power supply line, could be attached to one circuit board. Two PT100 temperature sensors are used to monitor the overall box temperature (fixed with M4 screws), see Figure 3. In addition several temperature sensors on the circuit boards measure the board temperatures. The dimensions of EBX 1 and EBX 2 are 122 x 134 x 140 mm (length x width x height). Each box has a mass of about 1.7 kg and a total power consumption of about 31-34 Watt (at 28 V).

The memory unit for electronic box 1 and 2 is shown in Figure 4 and contains a small circuit board with a memory card capable of storing several hours of sensor data. Because the memory unit has to survive the crash landing of the vehicle, the housing is made of stainless steel with a wall thickness of 8 mm. To further protect electronics and memory card the interior of the housing is completely filled with a potting compound.

The upper connector (9-pin D-Sub) is used for the connection to the PDU and the lower one (25-pin D-Sub) connects the unit to the corresponding electronic box. A DC/DC-converter on top of the memory unit converts the system voltage to the necessary voltage for the memory unit electronics. A PT100 temperature sensor is attached next to the DC/DC-converter to monitor the memory unit temperature. The memory unit is fixed to the ReFEx structure using six M5 screws. The memory unit dimensions are 90 x 102 x 56 mm (length x width x height), the weight is 1.7 kg and the total power consumption is about 3 Watt (at 28 V).

Electronic box and memory unit were developed in-house at the Supersonic and Hypersonic Technologies Department of DLR in Cologne.

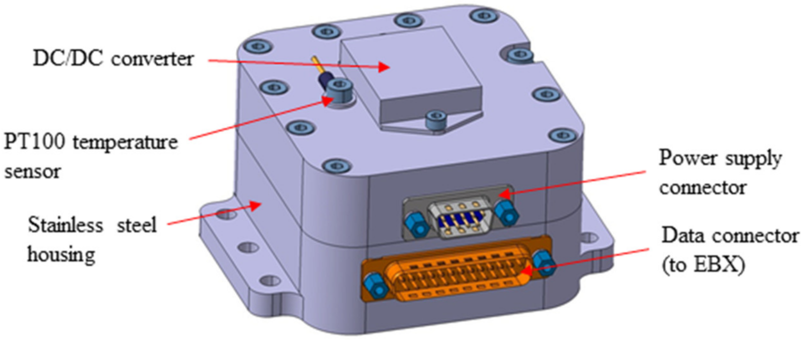

Figure 4: Memory unit for electronic boxes (dimensions 90 x 102 x 56 mm)

2.3 Fibre Optic Sensing System

The fibre optic system that is presented in Figure 5, is used for temperature measurements via optic fibres. The fibres are equipped with fibre Bragg gratings (FBG) that reflect certain wavelengths of the injected laser light. If the optic fibre is heated at the position of a FBG, the FBG characteristics change due to the expansion of the fibre which leads to a shift in the reflected wavelength. The magnitude of the wavelength shift indicates the applied temperature. Because an expansion of the fibre can also be the result of a mechanical strain, it is important that the fibre is mechanically decoupled from the structure so that only temperature variations influence the FBGs. This is accomplished by routing the fibre through a small stainless steel tube. The tube can be glued to the structure, but the internal optical fibre remains loose.

An optical fibre can contain several temperature measurement locations because each FBG of the fibre reflects a different wavelength of the laser light. The maximum number of measurements per fibre depends on the temperature measurement range. The left image of Figure 5 shows the electronic box of the fibre optic system which contains all necessary electrical and optical parts. Overall four fibres can be attached to the electronic box and each fibre accommodates six temperature measurement locations. A 15-pin D-Sub connector is used for power connection to the PDU (28 V), for data connection to the DHS (measured data) and for lift-off and pulse-per-second signals (see also Figure 1). The 9-pin D-Sub connector is used for a connection to the FOS memory unit shown on the right image of Figure 5. The memory unit contains a ruggedized USB-stick for data storage which is able to survive the

DOI: 10.13009/EUCASS2019-690

vehicle impact. In addition to the memory unit the electronic box contains an SD-card for data storage, but this card is not protected in any way and therefore may not survive the vehicle impact.

Electronic box and memory unit housings are made of aluminium and are fixed to the structure with four screws each. The dimensions of the FOS electronic box are 174 x 160 x 65 mm (length x width x height). The weight is 1.4 kg and the total power consumption is 4.5 Watt (at 28 V). The memory unit is much smaller with dimensions of 106 x 66 x 46.5 mm and it has a weight of 0.3 kg and negligible power consumption. The fibre optic system (electronic box and memory unit) is provided by the Canadian company MPB Communications Inc. [7].

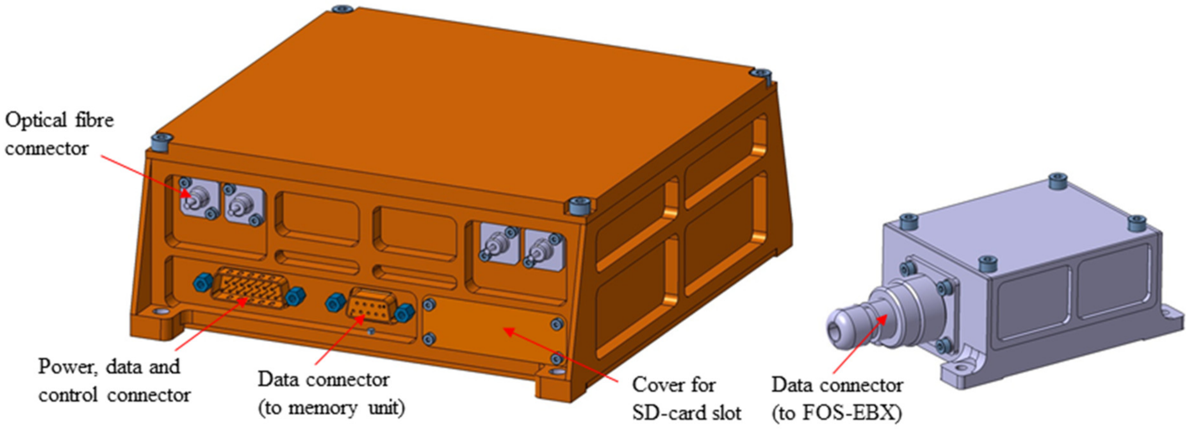

Figure 5: Fibre optic sensing electronic box (left) and memory unit (right)

2.4 Optical Cameras

For the optical cameras the RunCam Split 2s model shown in Figure 6 is used. This camera consists of a lens module (containing lens and CMOS chip) and a small corresponding circuit board which contains electronics and a memory card (SD-card). The dimensions of the board are 38 x 38 mm. Both parts are connected by a short cable.

Figure 6: RunCam Split 2s lens module and circuit board

The lens module is integrated into the front camera fin as shown in Figure 7. The necessary optical access is provided by a quartz glass window. The fin structure is attached to the cylindrical ReFEx module using an aluminium camera fin adapter and six M4 screws (right image of Figure 7). The camera lens module itself is fixed to a camera holder made of PEEK (Polyetheretherketon).

This material has a very low thermal conductivity (about 0.25 W/(mK)) and acts as an insulation between the hot camera fin structure which is exposed to the supersonic flow, and the camera lens module which can only withstand temperatures up to about 50°C. The fin dimensions are 53 x 40 x 21 mm (length x width x height), at which the height is measured between the cylindrical module surface and the upper fin edge, see Figure 7.

Figure 8 shows the camera fin assembly for the rear cameras which are located at the end of the vehicle above the wings, see Figure 2. The principle design is similar to the front camera fins, but the dimensions are slightly larger with 72 x 36 x 28 mm (length x width x height) at which the height definition is shown in Figure 8. The fin structure material for front and rear cameras depends on the expected structural temperatures due to aerothermal heating. Possible materials are stainless steel, aluminium or copper. The final decision will be made using thermal numerical analyses. The front cameras looking backwards towards the wings will record the complete flight from lift-off until touchdown. The rear cameras looking in flight direction are covered by the vehicle fairing and will therefore only record video after fairing separation.

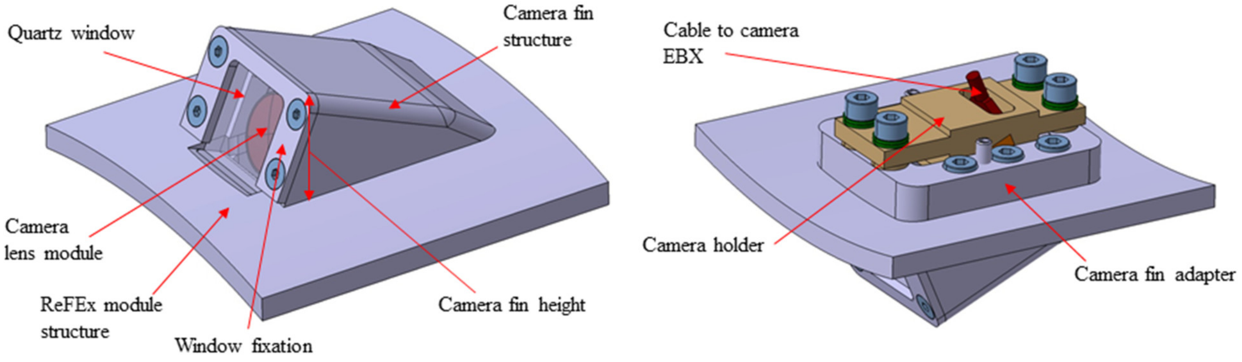

Figure 7: Front optical camera fin assembly

Figure 9 shows the electronic box for the optical cameras. Overall there are four of these boxes, one for each camera lens module. The boxes contain the camera circuit board with the memory card shown in Figure 6. As the memory card has to survive the vehicle impact, the box is manufactured from stainless steel with a wall thickness of 8 mm and the interior is filled with a potting compound. The electronic box has several electrical connections shown in Figure 9.

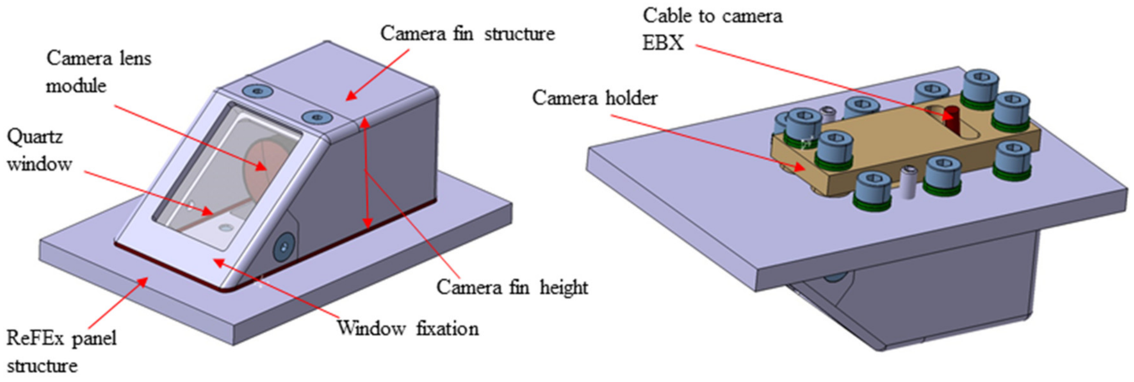

Figure 8: Rear optical camera fin assembly

A 9-pin D-Sub connector is used for the power connection to the PDU. The DC/DC-converter on top of the electronic box converts the system voltage to the necessary voltage for the camera. A second D-Sub connector (15-pin) is used for camera control, e.g. start/stop recording and mode switching. In addition to video recording in HD-format on the memory card, the camera circuit board also has a video output in PAL-format. This video output is routed through the coaxial connector to the on-board TV multiplexer, see also Figure 1. Because ReFEx has two independent video transmitting channels, signals of two cameras can be transmitted real-time.

The lens module (camera fin) is connected to the electronic box by the cable seen in Figure 6. As this cable only has a length of a few centimetres, a short cable extension is used which is directly routed through a small feedthrough in the side wall of the electronic box. There is no dedicated connector for this cable. Because the electronic box is filled with a potting compound, the cable can be disconnected at the lens module side for integration.

The fourth connector at the front side of the electronic box is a 4-pin LEMO connector. This connector is used for two temperature signals (thermocouples). One thermocouple is located inside the electronic box on the camera circuit board to monitor its temperature. The second thermocouple is located at the lens module housing to monitor the temperature of the lens module. The thermocouple cable is routed together with the camera cable extension to the feedthrough in the electronic box.

At the back side of the electronic box (image on the right in Figure 9) a small hatch is used to be able to connect a micro USB-cable to the camera circuit board. The USB-connection is used to transfer recorded video data or to delete the memory card. If no USB-connector is attached, the hatch is closed by a small cover.

The electronic box dimensions are 82 x 98 x 51 mm (length x width x height). The box has a weight of about 1.4 kg and is fixed to the structure with six M5 screws. The overall power consumption is about 4.5 Watt.

DOI: 10.13009/EUCASS2019-690

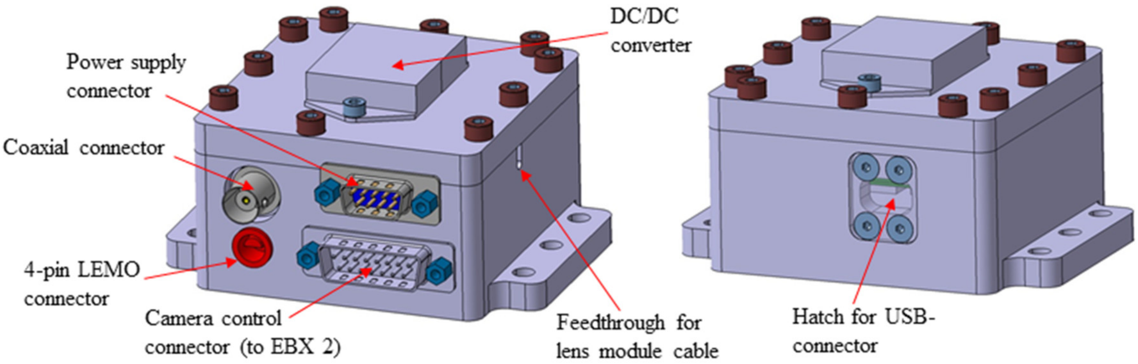

Figure 9: Optical camera electronic box

2.5 Infrared Cameras

Two infrared cameras are used to monitor the upper surface temperature of the front control surfaces (canards). The cameras are integrated into small fins with an infrared transparent window (zinc-selenide) located above the canards as shown in Figure 2. The planned infrared camera is a Lepton 3.5 of the FLIR Company. This infrared camera is very small with dimensions of only 10.5 x 12.7 x 7.1 mm (Figure 10) and therefore it fits well into the small camera fin. Further specifications are 160 x 120 active pixels, a measurement range up to about 400°C, very low power consumption and a wide operational temperature range between -10°C and 80°C. The effective frame rate is set to 8.7 Hz to be compliant with US export restrictions.

Figure 10: FLIR Lepton 3.5 infrared camera

Figure 11 shows the infrared camera fin with the zinc-selenide window. The fin has a length of 70 mm, a width of 29 mm and a height of 14 mm. As already mentioned for the optical cameras the fin material depends on the expected structural temperatures due to aerothermal heating. Therefore, the final material selection has to be done using thermal numerical analyses. Similar to the optical cameras, the infrared camera itself is attached to a PEEK (Polyetheretherketon) holder inside the camera fin for thermal insulation purposes.

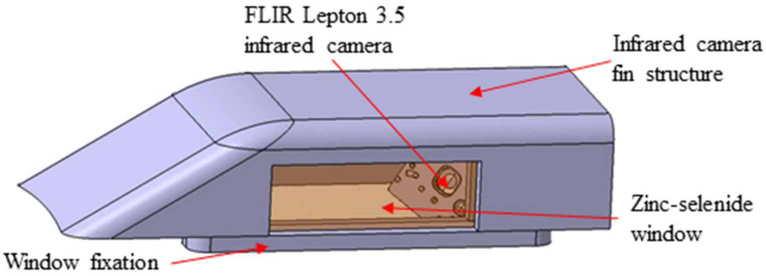

Figure 11: Infrared camera fin

In addition to the two infrared camera fins on the upper part of the vehicle (Figure 2), two additional dummy fins without cameras are used for the lower vehicle part to ensure vehicle symmetry.
Infrared camera control, data recording and data transfer are accomplished by the use of a small microcontroller with an appropriate memory card for data storage. The microcontroller circuit board and the memory card are integrated

DOI: 10.13009/EUCASS2019-690

into an electronic box similar to the optical camera electronic box, to ensure that the memory card will survive the vehicle impact. A part of the infrared images is also sent via telemetry.
Unfortunately, the design of infrared camera fin and corresponding electronic box is still ongoing at the time of publication. Therefore, no further information can be provided about the detailed design.

2.6 Breakout-Boxes

The breakout-boxes are used as interconnection between the individual sensors and the electronic boxes presented in section 2.2. Each sensor cable terminates in a 2-pin or 4-pin LEMO connector (type FFA-0S) which is attached to the receptacle (type ERA-0S) at the corresponding breakout-box. There are two breakout-box versions, one version with 10 LEMO connectors (Figure 12) and a second version with 14 LEMO connectors.

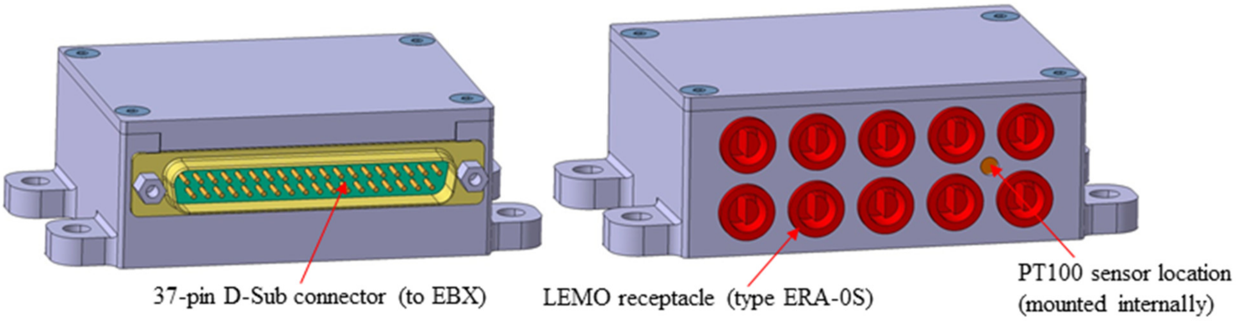

Figure 12: Breakout-box with 10 LEMO connectors

The connection to the corresponding electronic box (Figure 3) is done using a 37-pin D-Sub connector. Each EBX circuit board for sensor data acquisition has its own breakout-box, see Figure 1. Overall there are six breakout-boxes with 10 connectors and four breakout-boxes with 14 connectors. Each breakout-box contains one or two internal PT100 temperature sensors which are located between the LEMO connectors as shown in Figure 12. These sensors are used to monitor the breakout-box temperature and for cold-junction compensation of the attached thermocouples.
The breakout-boxes are manufactured from aluminum. Dimensions of the breakout-box shown in Figure 12 are 63 x 97 x 29 mm (length x width x height). The box with 14 connectors has a height of 40 mm. The mass of the box is about 0.28 kg. Both box-versions are fixed with four M5 screws.

2.7 Flight Instrumentation Sensors and Interfaces

Because the structure of ReFEx is completely metallic (titanium, aluminum) the integration of the sensors into the structure can be done using simple screw connections. In the following the sensors and their fixation are described in more detail.

Pressure sensors:
To measure the static pressure on the outer surface of the vehicle, absolute and differential pressure sensors are used.
The final sensor type is still under consideration, but a good option is the ETL-76A-190M sensor of the Kulite Company for absolute measurements. This sensor is available for different measurement ranges and is mountable via M5 thread. It has an amplified output signal (5 V full-scale) and works with a supply voltage of 12 ± 4V. Therefore, no precise regulation or measurement of the supply voltage is necessary for the pressure measurement.
Although the sensor has a compensated temperature range of -40°C to 175°C it is best to keep the sensor temperature as constant as possible, because even in the compensated range the sensor has a non-negligible thermal zero and thermal sensitivity shift.
As the temperatures on the vehicle outer surface exceed the compensated temperature range depending on the sensor location, the pressure sensors are not mounted directly at the vehicle surface, which also minimizes thermal signal shifts. Instead they are mounted to aluminium sensor holders which are fixed to the inner vehicle structure and are connected to the corresponding pressure port at the vehicle surface via flexible tubing. The temperatures of these sensor holders are monitored by PT100 temperature sensors, to be able to compensate thermal signal shifts which are caused by sensor heating via structural heat conduction. The used pressure ports are similar to the one shown on the right side of Figure 15.

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Heat flux sensors:
The sensors used for measuring total heat flux are heat flux microsensors of the Vatell Company. This sensor is available in a low-temperature (type HFM-7E/L) and a high-temperature (type HFM-7E/H) version. The sensor head for both versions, which incorporates a thin-film thermopile for the heat flux measurement, has a length of 24.5 mm, a front diameter of 6.32 mm and is mounted with a M12 capture nut. The sensor temperature is measured by a resistance temperature sensing element (RTS) which consists of a pure platinum thin film deposited in a loop pattern around the outer edge of the sensor face. This temperature is used for a correction of the heat flux (thermopile) signal which depends on sensor temperature. The sensor head of the high temperature sensor version is shown in Figure 13.

Figure 13: Heat flux microsensor HFM-7E/H sensor head with M12 capture nut

They are mounted flush with the vehicle surface using small metallic sensor interfaces because the wall thickness of the vehicle structure is not sufficient to directly mount the sensors using the M12 capture nuts. The sensor interface material is chosen according to the structure material at the sensor location (e.g. aluminium). The low temperature version of the sensor can withstand temperatures up to 350°C at the sensor face. For higher temperatures the high-temperature version can go up to 600°C at the sensor face.

Temperature sensors:
Different kinds of temperature sensors are used for the ReFEx flight instrumentation. The temperature of the flight instrumentation units (e.g. EBX 1 or breakout-boxes) are measured by PT100 temperature sensors. These sensors are able to measure temperatures up to 250°C which is sufficient for components mounted to the inner vehicle structure.
The second type of temperature sensors are type K thermocouples made from twisted thermocouple wires with Polytetrafluorethylen (PTFE) insulation. The two wires are welded at one end to form the thermocouple junction. This kind of thermocouple is also only able to measure temperatures up to about 250°C (limited by the maximum temperature of the PTFE) but is smaller than the PT100 sensors. They are used to measure the internal temperatures of optical and infrared cameras including their electronic boxes where the application of PT100 sensors is not possible because of their size.
For the measurement of higher temperatures two types of thermocouples are used. The first one is similar to the PTFE insulated thermocouple mentioned before, but uses glass fibre insulation instead of PTFE. Equipped with an eyelet or a small thread for fixation, these thermocouples can measure temperatures up to about 480°C. For even higher temperatures sheathed type K thermocouples with 0.5 or 1 mm diameter are used which measure temperatures up to 1100°C. The sheath itself is made from high temperature steel (Inconel). For example these thermocouples are used to measure the temperature of the fin leading edges.
The surface temperature of the vehicle is measured by type E coaxial thermocouples which are applicable up to 900°C. These thermocouples are mounted flush with the vehicle surface and are fixed by a screw connection. Coaxial thermocouples consist of a small tube and a pin which are separated by a few micrometres of electrical insulation. Tube and pin represent the two active legs of a thermocouple. By grinding the head of the probe, a junction between the two metals is achieved. The thin grinding burr represents the thermal active part which, due to its small mass, yields a fast response time of the probe in the order of a few microseconds. Because the diameter of the probe is small (about 1.9 mm) the grinding of the probe head can also be used to adjust the thermocouple to the surface geometry. The coaxial thermocouples used for ReFEx additionally contain a second temperature measurement at the back end of the sensor (normal thermocouple).
Using front and back end temperatures of the sensor, the heat flux at the location of the coaxial thermocouple can be calculated assuming one-dimensional heat conduction. For short measurements (in the order of seconds) the heat flux can also be calculated using only the front end temperature. In this case a semi-infinite wall is assumed, meaning that the back end of the sensor has to remain at a constant temperature during the measurement [8]. A short measurement time also minimizes the influence of radial heat conduction (one-dimensional heat conduction is assumed). For the ReFEx flight with a flight time of several minutes, the sensor back end will not remain at a constant temperature and therefore both temperatures are used for the heat flux evaluation.

DOI: 10.13009/EUCASS2019-690

Accelerometer sensors:
Three accelerometer sensors are used to measure accelerations at different locations. One sensor is integrated into each of the wings to measure possible wing structure oscillations. A third sensor is located at the center of the vehicle to measure overall vehicle accelerations. Each sensor measures the acceleration in all three axes.

Sensor positions:
Figure 14 shows an overview of the sensor positions on the ReFEx vehicle. Most sensors are distributed on four main instrumentation lines (top, bottom, left and right). In addition several sensors are grouped to measure the pressure distribution in the canard wake on one side, the temperatures of wing, fin and canard leading edges, the base pressure distribution and the pressures at the nose tip to determine the freestream parameters using the FADS system. The applicability of the canard leading edge temperature measurement using thermocouples is to be confirmed (TBC) at the time of publication. One difficulty is the routing of the thermocouples through the hollow shaft of the canard actuator without the wires being damaged during rotation or interfering with the canard movement.
The shown sensor layout represents the status at the time of PDR and therefore may be updated until the critical design review (CDR).

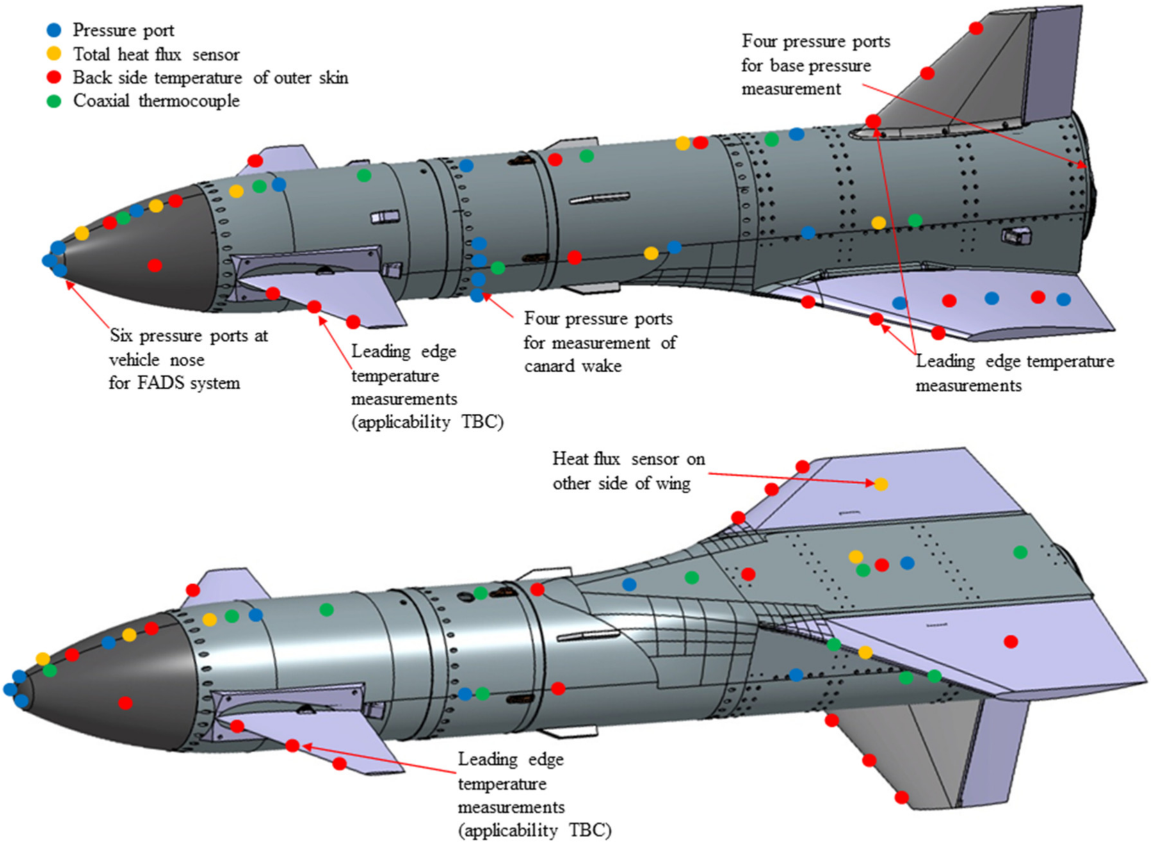

Figure 14: Overview of flight instrumentation sensors on ReFEx vehicle (PDR status)

2.8 Flush Airdata Sensing (FADS) System

The FADS system comprises of six pressure ports at the spherical nose tip. Because of high temperatures at the nose tip during re-entry, the actual pressure sensors are not fixed to the nose structure due to their limited working temperature range. Instead they are mounted to a small aluminium sensor holder that is located in the nose section of the vehicle and they are connected to the pressure ports at the nose tip via flexible tubing. Although the sensor holder is not directly connected to the hot nose structure, it will heat up due to structural heat conduction and radiation. As zero offset and sensitivity of the pressure sensors vary with temperature, the sensor holder is equipped with two PT100 temperature sensors. Using the temperature measurements and a precise thermal calibration of the pressure sensors before flight, the thermal zero and thermal sensitivity shifts of the sensor output signals can be incorporated in the pressure measurement.

The pressure ports at the nose tip consist of small boreholes with 0.5 mm diameter in the spherical part of the nose structure. To connect the pressure ports to the pressure sensors, two approaches are under consideration.

One approach is to braze/weld a short piece of metallic tubing to the nose structure and attach flexible tubing for the connection to the pressure sensor, see sketch on left side of Figure 15. A second solution is to use small cylindrical stainless steel pressure ports which can be screwed to the nose tip structure. These pressure ports would also be connected to the pressure sensors via flexible tubing. An example is given on the right image of Figure 15. For both solutions the length of the metallic tubing at the pressure port has to be chosen in such a way, that the temperature at the transition to the flexible tube does not exceed the maximum working temperature of the flexible tube material. As the pressure sensor holder is located in the nose section close to the pressure ports at the nose tip, the flexible tubing is very short which minimizes pneumatic lag in the pressure tubing and ensures a fast response time of the pressure measurement. The applicability of these solutions depends on nose tip design (e.g. wall thickness) and accessibility of the nose interior to manufacture or mount the pressure ports.

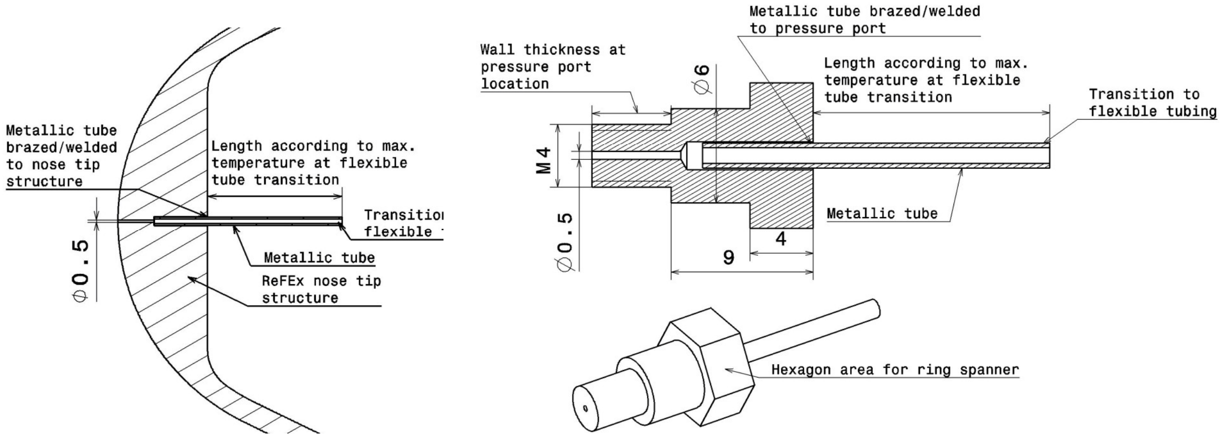

Figure 15: Sketches of a metallic pressure tube directly attached to nose structure (left) and possible pressure port design for nose tip (right)

The distribution of the pressure ports at the nose tip depends on the maximum angle of attack and sideslip. The distribution will be similar to the X-33 FADS system presented in [9], see Figure 16. This system was designed to give good sensitivity for local angles of attack varying from –20° to 45°, and angles of sideslip of up to ± 20°.

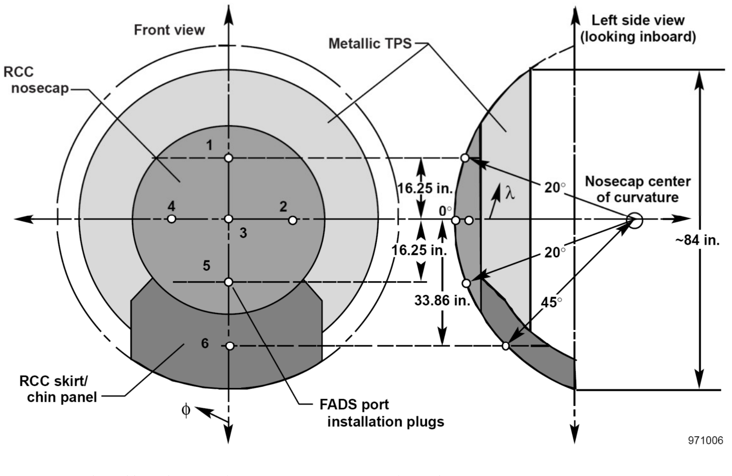

Figure 16: Distribution of pressure ports for the X-33 FADS system [9]

The FADS system is used to determine the vehicle angle of attack, angle of sideslip, static pressure and dynamic (impact) pressure. These parameters are calculated using measured pressures and a dedicated software algorithm. The FADS sensor data acquisition (pressure measurements) and the execution of the algorithm software are conducted by circuit board 1 of EBX 1. There are two options for the algorithm.

The first one is described in detail in [9] and is called triples algorithm. This approach allows the calculations for local angle of attack to be decoupled from the calculations for local angle of sideslip using only pressure ports on the

DOI: 10.13009/EUCASS2019-690

vertical or horizontal axis. The local angle of attack and sideslip are thereby the local flow incidence angles sensed by the FADS system. To evaluate the true (free-stream) angle of attack and sideslip effects like bow shock flow deflection and body-induced upwash and sidewash have to be taken into account. This is done by introducing a calibration parameter which is dependent on Mach number. The Mach number is evaluated using static and impact pressure. The overall system of equations for the triples algorithm is nonlinear and therefore has to be solved iteratively. Due to the relatively simple equations, the triples algorithm is very fast and can be used as a real-time system.

The second option for the FADS algorithm is a simple database with pressure values for several combinations of Mach number, angle of attack and angle of sideslip. The evaluation of the aerodynamic parameters is done by minimizing the root-mean-square (RMS) deviation between measured pressure values and database values. Because this approach has to evaluate a high number of comparisons with database values, the calculation time is higher than for the triples algorithm. This approach was applied for the SHEFEX-II post-flight analyses using a numerical database [10].

Both approaches require an extensive wind tunnel campaign to determine the calibration parameters for the triples algorithm or to generate the necessary database for the RMS approach. The wind tunnel test matrix has to include the complete expected angle of attack, angle of sideslip and Mach number range. Before conducting the wind tunnel tests, a CFD-database will be created with the DLR Tau-code [11] which is used to evaluate the applicability of the two approaches.

3. Summary

The German Aerospace Center is preparing a sub-scale reusability flight experiment called ReFEx that is planned to be launched in 2022. The main objective is the demonstration of a controlled autonomous re-entry flight from hypersonic speed down to subsonic velocities. In addition different key technologies for reusable first stages will be tested during flight. To gather aerodynamic and aerothermodynamic flight data, the vehicle is equipped with a large number of different sensors, together with corresponding data acquisition systems. In the post-flight analyses recorded data can be used to evaluate vehicle performance and health status during flight. Because flight experiments are generally rare due to their high costs, the acquired flight data also present valuable information for the validation and improvement of numerical tools for the vehicle design of future missions.

Starting with an overview of used sensors and main instrumentation units, this paper describes all different parts of the flight instrumentation for the ReFEx vehicle. Overall 131 sensors are acquired by two electronic boxes which perform signal conditioning, amplification and analogue-to-digital conversion for the analogue sensor signals. The sensors include pressure, temperature, heat flux and accelerometer sensors. Sensor data are sent to the ground station via telemetry and stored on-board on dedicated memory units with higher sampling frequency. Because the vehicle does not contain a parachute system, all memory units are designed to survive a hard impact. A fibre optic system is used for temperature measurements in addition to the standard temperature sensors like thermocouples. This system is based on fibre Bragg gratings and consists of an electronic box with four attached optic fibres and a memory unit.

The flight instrumentation also includes four optical cameras to record videos of the complete flight. Lens modules of the cameras are integrated into small fins which are located at the vehicle front and rear end. They are connected to corresponding electronic boxes that contain camera circuit boards and memory cards. These boxes are also designed to withstand the vehicle impact. ReFEx contains two video transmitting channels, so that the signals of two video cameras can be transmitted real-time.

Temperature distributions on the upper sides of the front control surfaces (canards) are measured by two small infrared cameras which are integrated into fins with infrared transparent windows located above the canards. Two dedicated electronic boxes are used for camera control and data storage. A part of the measured infrared data is also sent to the ground station via telemetry.

Six pressure sensors at the vehicle nose tip form a flush airdata sensing system that is used for a determination of angle of attack, angle of sideslip, static pressure and dynamic (impact) pressure. Pressure sensor signal recording and execution of the corresponding software algorithm are conducted by one of the electronic box circuit boards.

Although the on-board hybrid navigation system also determines these parameters, values provided by the flush airdata sensing system are used as a second source of information. In contrast to the hybrid navigation system, calculated values also include the actual wind conditions at the vehicle location which is especially important at lower flight speeds in the sub- and transonic regime.

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