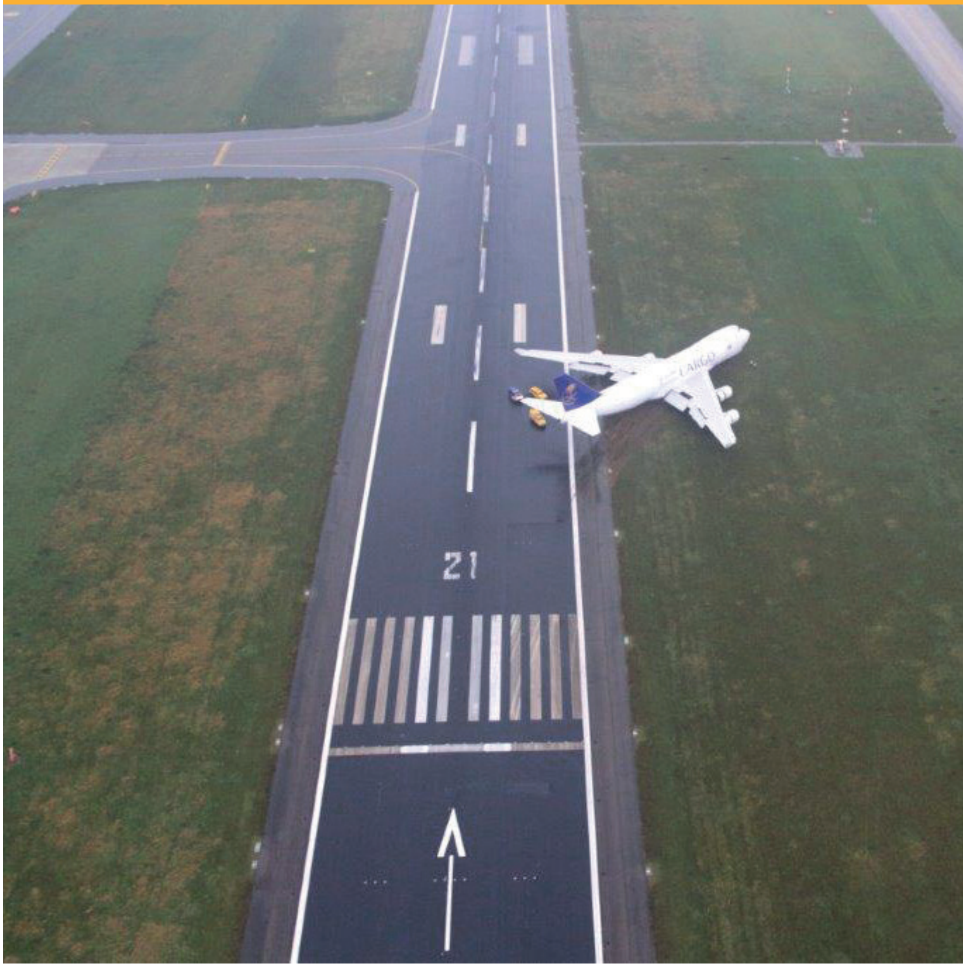
DUTCH
SAFETY BOARD

# Runway excursion after loss of thrust at low speed



# Runway excursion after loss of thrust at low speed

*The Hague, March 2020*

*The reports issued by the Dutch Safety Board are open to the public and available on www.safetyboard.nl.*

*Cover photo: Aviation police*

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| | | | |
|---|---|---|---|
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N.B. This report is published in the English language with a separate Dutch summary. If there is a difference in interpretation between the report and the summary, the report text will prevail.

# CONTENT

# ABBREVIATIONS

| | |
|---|---|
| AGB | Accessory Gear Box |
| AMM | Aircraft Maintenance Manual |
| ASDA | Accelerate Stop Distance Available |
| ATC | Air Traffic Control |
| ATIS | Automatic Terminal Information Service |
| ATOW | Actual Take-off Weight |
| ATP | Acceptance Testing Procedure |
| ATPL(A) | Airline Transport Pilot License (aeroplane) |
| | |
| BKN | Broken |
| BSCU | Brake System Control Unit |
| | |
| CG | Centre of Gravity |
| CMM | Component Maintenance Manual |
| CRM | Crew Resource Management |
| CSN | Cycles Since New |
| CVR | Cockpit Voice Recorder |
| | |
| DEP | Departure |
| DEST | Destination |
| DOW | Dry Operating Weight |
| | |
| EGT | Exhaust Gas Temperature |
| EHBK | Maastricht Aachen Airport |
| EPR | Engine Pressure Ratio |
| | |
| FADEC | Full Authority Digital Engine Control |
| FAR | Federal Aviation Regulations |
| FCOM | Flight Crew Operations Manual |
| FCTM | Flight Crew Training Manual |
| F/D | Flight Director |
| FDR | Flight Data Recorder |
| FL | Flight Level |
| FOD | Foreign Object Damage |
| Ft | Feet |
| | |
| GE | General Electric |
| | |
| HPa | Hectopascal |
| HPC | High Pressure Compressor |
| HPT | High Pressure Turbine |

| | |
|---|---|
| ICAO | International Civil Aviation Organization |
| IR(A) | Instrument Rating (Aeroplane) |
| | |
| KNMI | Dutch Meteorological Office |
| | |
| LE | Leading Edge |
| LH | Left Hand |
| LPC | License Proficiency Check |
| LPT | License Proficiency Training |
| | |
| METAR | Meteorological Aerodrome Report |
| MSL | Mean Sea Level |
| MTOW | Maximum Take-Off Weight |
| | |
| N1 | The rotational speed of the low speed spool of an engine, expressed as a percentage of a nominal value |
| NM | Nautical Mile |
| NTSB | National Transportation Safety Board (USA) |
| | |
| OEJN | King Abdulaziz International Airport |
| OM | Operations Manual |
| OPC | Operator Proficiency Check |
| OPT | Operator Proficiency Training |
| OVC | Overcast |
| | |
| PF | Pilot Flying |
| PM | Pilot Monitoring |
| PW | Pratt and Whitney |
| | |
| QRH | Quick Reference Handbook |
| | |
| RR | Rolls Royce |
| RTO | Rejected Take-Off |
| | |
| SIGMET | Significant Meteorological Information |
| SMS | Safety Management System |
| SOP | Standard Operating Procedures |
| | |
| TAF | Terminal Aerodrome Forecast |
| TO/GA | Take-off/Go-around |
| TODA | Take-Off Distance Available |
| TORA | Take-Off Runway Available |
| TOW | Take-Off Weight |
| TR | Trainee |
| TRA | Throttle Resolver Angle |
| TRI | Type Rating Instructor |
| TSN | Time Since New |

| | |
|---|---|
| UTC | Coordinated Universal Time (Greenwich mean time) |
| | |
| VBV | Variable Bleed Valve |
| $V_{MCG}$ | Minimum control speed of an aeroplane on ground |
| VSV | Variable Stator Vane |

# GENERAL OVERVIEW

| | |
|---|---|
| Identification number: | 2017118 |
| Classification: | Serious incident |
| Date, time of occurrence: | 11 November 2017, around 22.36 hours[1] |
| Location of occurrence: | Maastricht Aachen Airport (EHBK) |
| Registration: | TC-ACR |
| Aircraft type: | Boeing 747-400 ERF |
| Aircraft category: | Aeroplane |
| Type of flight: | Commercial cargo flight |
| Phase of operation: | Take-off |
| Damage to aircraft: | Substantial |
| Flight crew: | Two (captain and first officer) |
| Other crew: | Two (technician and load master) |
| Passengers: | None |
| Injuries: | None |
| Other damage: | Deep tracks made by the landing gear in the soft ground of the airfield |
| Light conditions: | Darkness |

1 All times are UTC, unless otherwise specified. Local time is UTC+1 hour.

# SUMMARY

TC-ACR, a Boeing 747-400 ERF, was scheduled to make a cargo flight from Maastricht Aachen Airport in the Netherlands to King Abdulaziz International Airport in Jeddah. After the aircraft was loaded, the captain, who was pilot flying, taxied to Runway 21 and initiated a rolling take-off. He advanced the thrust levers and, when the engines had stabilised, he pushed the TO/GA switches, causing the engines to accelerate to the selected take-off thrust. The aircraft had accelerated to approximately 30 knots when the outboard engine on the right side (engine #4) suddenly lost power. The aircraft veered to the right due to the resultant asymmetric thrust. The thrust levers were not immediately retarded to idle, so this asymmetric thrust continued. Attempts to steer the aircraft back to the centreline by means of nose wheel steering and differential braking, were unsuccessful. The aircraft could not be controlled. It veered off the runway and continued on into the soft ground on the right-hand side of the runway. The resistance of the soft ground and the eventual retardation of the thrust levers caused the aircraft to come to a standstill. None of the crew was injured. The aircraft sustained substantial damage. The runway excursion was caused by prolonged asymmetric thrust, due to the loss of thrust on engine #4 at low speed. The loss of engine thrust was caused by a compressor stall.

The only way to arrest a deviation resulting from asymmetric thrust below the speed at which the rudder becomes effective, is to promptly retard the thrust levers to idle. That has not happened in this occurrence; it took about eight seconds for the thrust levers to be retarded. Not retarding the thrust levers was most likely due to the ‘startle effect’ on the crew. The startle effect caused the crew to deviate from standard procedures. The use of noise cancelling headsets could also have played a role in this scenario.

Following the loss of thrust on engine #4, the crew did not respond as they had been trained for and their actions were not in accordance with the RTO procedures described in the manuals. Flight crews are trained to deal with unexpected rejected take offs due to an engine failure. However, the element of surprise in training in a simulator setting is very limited. The flight crews are aware that a failure is about to occur. This greatly diminishes the element of surprise during simulator sessions. As a result, the chance that the ‘startle effect’ occurs during the training is minimal.

The cause of the compressor stall has not been extensively investigated. However, some engine components have been examined. While some of them clearly needed to be overhauled as a result of wear (due to the age of the engine), none of them could be linked to the compressor stall. The compressor stall might have been a result of the overall technical state of the engine.

# 1 FACTUAL INFORMATION

## 1.1 History of the flight

On Saturday 11 November 2017, the aircraft, a Boeing 747-400 ERF with the registration number TC-ACR was parked on cargo apron B at Maastricht Aachen Airport (EHBK). The aircraft was scheduled to depart at 21.55 hours to make a cargo flight (SV916) to King Abdulaziz International Airport in Jeddah (OEJN). The crew consisted of a captain, a first officer, a technician and a load master. The aircraft had arrived from Jeddah earlier that day, at 10.26 hours. According to the combined flight and technical log, no additional defects or anomalies were recorded during the inbound flight.

The aircraft was refuelled with 57,753 litres of fuel. It was loaded with 85,110 kilograms of cargo, in accordance with the loading instruction report. The captain stated that he had felt unduly pressured, due to the night flight restrictions at EHBK. The handling agent had urged him to depart, as the airport was due to close at 22.00 hours. Despite the urgency of the situation, the captain first called the airline's Operations Department for consultation. As a result of this consultation and the granting of an exemption by the airport authorities extending the take-off deadline until 23.00 hours, the crew was ready for departure. The captain (pilot flying) was seated on the left side of the cockpit, the first officer (pilot monitoring) was seated on the right side, the technician was seated in the cockpit, in the observer's seat (behind the flight crew), and the load master was seated in the cabin area. The captain and the first officer were wearing their headsets and were communicating with one another via the intercom system. The first officer left one ear uncovered by the headset. The technician and the load master were not wearing headsets.

The flight crew performed the flight briefing and completed the pre-flight procedures. Around 22.19 hours, when all pre-flight preparations had been completed, the crew reported to Air Traffic Control (ATC) that they were ready for push back and requested clearance for departure.

Around 22.29 hours the aircraft was cleared for start-up. Once the pre-start checklist had been completed, the engines were started. All four engines took the same time to start up and gave identical indications during the start-up sequence. After the start-up, the engines stabilised at their normal values. Since Apron B is only around 300 metres from the start of Runway 21, the crew decided to complete both the before taxi checklist as well as the before take-off checklist before taxi commenced. The crew did not observe any anomalies at this time. According to FDR data, the normal engine warming-up criteria were met. ATC cleared the aircraft for taxi at 22.34 hours, after which TC-ACR taxied to Runway 21. During taxi, the crew made some remarks about how dark it was (the sky was overcast so there was no moonlight, and there were few other sources of illumination). While taxiing to Runway 21, the aircraft was cleared for take-off at 22.35:35 hours.

After some general conversation between the captain and the first officer about the flight, the aircraft entered Runway 21 and a synthetic voice reported 'on Runway 21' at 22.36:26 hours. The aircraft maintained a groundspeed of 5 kts. Five seconds later, the first officer called 'Set thrust', after which the captain called 'Take off', at 22.36:32 hours. The captain advanced the thrust levers to approximately 70% N1 and the sound of engines spinning up was audible on the CVR. Once the engines had stabilised at around 70% N1, the captain pushed the TO/GA switches, causing the engines to accelerate to the selected take-off power. Meanwhile, the aircraft's ground speed was increasing. At 22.36:36 hours, the captain called 'Set take-off thrust'. Four seconds later, at around 22.36:40 hours, a loud noise was audible on the CVR. The first officer, the technician and the load master stated that they had heard a loud bang from outside the aircraft.

The flight crew was interviewed shortly after the incident. In his statement, the captain indicated that he had not heard the bang as he was wearing an active noise cancelling headset. The captain noticed that the aircraft was yawing to the right, but at that moment he did not know what was causing this. He attempted to correct this deviation, using the nose wheel steering tiller and by applying left rudder. He then applied the left-hand brake pedal. The aircraft moved a little to the left, but almost instantly resumed its deviation to the right. When the captain noticed that the aircraft was moving to the right side of the runway he concluded that it was uncontrollable. He then took the decision to abort the take-off, and applied both brake pedals. He stated that he immediately pulled the thrust levers back and held them, in case the autothrottle disconnect button failed to respond. In spite of these actions, the aircraft veered off the runway and rolled onto the grass. At 22.37:02 hours the engines were switched off. None of the four persons on board were injured.

The first officer had been monitoring the instruments during the take-off. He stated that he had not noticed any anomalies on the instruments. In his role as pilot monitoring, he was required to make the 80 kts call when the aircraft reached that speed. Therefore his attention was shifted from the engine instruments to the air speed indicator. When he heard the loud noise from the right side of the aircraft and noticed that the aircraft was veering to the right, he immediately called: 'Off, abort, abort, abort'. He stated that, while he did not know what had happened, he was convinced that the take-off had to be aborted. He also stated that he had not operated any control devices in an attempt to help the captain keep the aircraft on the runway.

Some witnesses on the ground heard a loud bang shortly after the start of the take-off roll. Since it was dark, nobody knew what had caused this noise.

The aircraft had veered off the runway and had come to a standstill in the soft soil of the grass field on the right side of Runway 21. After the occurrence, it was found that all of the aircraft's engines were in reverse and its speed brakes were up.

The next day, the aircraft was off-loaded and defueled. It was then recovered from the area of soft ground in which it had come to rest, and towed to a parking stand.


*Figure 1: Aerial pictures of the runway excursion. (Source: Aviation police)*

## 1.2 Injuries to persons

None.

## 1.3 Damage to aircraft

The aircraft sustained substantial structural damage as a result of the occurrence. This damage consisted of several bent and deformed skin panels and stringers. In addition, the nose wheel well web had several deformations on the right- and left-hand sides. As a result of this damage, the manufacturer of the aircraft had to carry out major repairs at Maastricht Aachen Airport.

## 1.4 Other damage

Deep tracks left by the aircraft's gear in the soft ground of the airfield.

## 1.5 Personnel information

### 1.5.1 Captain

| | |
|---|---|
| Age | 63 |
| Nationality | Turkish |
| License | ATPL(A), valid until 28 February 2018 |
| Ratings | B-747 400, IR |
| Medical certificate | Class 1, valid until 2 March 2018 |
| Total flight hours | 18,550:40 |
| Flight hours on type | 3,030:50 |
| Flight hours previous 30 days | 79:42 |
| Rest hours before the flight | 55:59 |

### 1.5.2 First officer

| | |
|---|---|
| Age | 42 |
| Nationality | Turkish |
| License | ATPL(A), valid until 31 January 2018 |
| Ratings | B-747 400, IR, TRI |
| Medical certificate | Class 1, valid until 10 April 2018 |
| Total flight hours | 4,462:58 |
| Flight hours on type | 2,042:43 |
| Flight hours previous 30 days | 64:46 |
| Rest hours before the flight | 55:59 |

## 1.6 Aircraft information

| | |
|---|---|
| Make and model | Boeing 747-400 ERF |
| Serial number | 32866 |
| Year of manufacture | 2002 |
| Airworthiness Review Certificate | Valid until 16 June 2018 |
| Engines | 4 GE CF6-80C2B5F |
| Engine #4 | Ser.no. 706509, TSN 42,617.01, CSN 6,953 |
| Weights and balance | DOW 160,902 kg, MTOW 412,769 kg |
| | ATOW 309,712 kg |
| | Index 53.4, CG 21.3% |
| Maintenance status | Airworthiness certificate valid until 16 June 2018 |
| Deferred items | One item, non-relevant |

## 1.7 Meteorological information

The crew obtained relevant weather information from the ground handling staff. This consisted of updated reports (METAR), forecasts (TAF), significant weather charts (SIGMET) and wind charts for the flight. The prevailing weather conditions during the occurrence were as follows: wind direction 250 degrees (varying from 210 to 300 degrees) with a strength of 3 kts, visibility 8 kilometres, clouds broken at 4,000 ft and overcast at 4,400 ft, temperature 5 °C, dew point 5 °C, the local air pressure adjusted to mean sea level was 1011 HPa.[2]

## 1.8 Communications

All ATC communication was carried out by Maastricht Tower. The details of all relevant communications are included in the transcript (Appendix A) and in section 1.1.

2 METAR EHBK 112225Z AUTO 25003KT 210V300 8000 BKN040 OVC044 05/05 Q1011.

## 1.9 Aerodrome information

Maastricht Aachen Airport has a single paved runway (03-21). The dimensions of this runway are 2,750 x 45 metres. Runway 21 has a displaced threshold of 250 metres. For large aircraft, such as the Boeing 747, the full length of the runway is available. This gives a TORA/TODA/ASDA of 2,750 metres. On each side of the runway there is an 8-metre-wide paved shoulder. Beyond these runway shoulders, there is soft soil with grass cover.

The runway surface consists of anti-skid asphalt. Runway friction measurements are carried out on Runway 03-21 annually. The last measurement prior to the date of the occurrence was carried out on 27 November 2017. Several measurements were carried out with 1 mm water on the runway, at different speeds and at different distances from the centreline. According to the report, Runway 21 exceeded the minimum required friction levels under all these conditions. Around the time of the occurrence, the runway surface was damp.

B-Apron, the cargo platform, is situated near the threshold of Runway 21. It can be reached via taxiway W1. The distance from an aircraft stand on B-Apron to the threshold of Runway 21 is approximately 300 metres.

The airport's opening hours for cargo flights are 06.00 to 22.00 hours, from Monday to Sunday. The airport authorities can grant a one-hour exemption, commencing at 22.00 hours.

## 1.10 Flight recorders

### 1.10.1 Flight Data Recorder

The aircraft was equipped with a solid-state flight data recorder (FDR), manufactured by Honeywell. Data from the FDR was successfully downloaded and verified. With the assistance of the aircraft's manufacturer, the following 'sequence of events' was created, based on FDR data.

FDR data showed that the aircraft was configured for a flaps 20 take-off. The magnetic heading increased as the aircraft turned right from the taxiway onto Runway 21. At 22.36:24 hours the throttle resolver angles (TRAs) were increased from 40 to 43 degrees, after which the engines' N1 stabilised at around 42%. At 22.36:31 hours the TRAs were increased from 43 to 56 degrees. The engines' N1 increased from around 42% to 74%, and the longitudinal (forward) acceleration increased as the aircraft began its take-off roll. Beginning at 22.36:33 hours, a small amount of left rudder pedal pressure was applied. The TRAs were increased again, starting at 22.36:40 hours and the engine N1 and longitudinal acceleration began to increase. The N1 of all four engines increased, this was uniform for engines #1 to #3 but more rapid in the case of engine #4. When the N1 of engine #4 reached 92%, the N1 values for engines #1 to #3 were 81.6%, 82.8% and 87% respectively. Around this time, left pedal input was removed, and the right pedal was applied.

Almost immediately after the TRAs were increased, at a ground speed of 30 knots and at 92% N1, there was a sudden drop in engine #4's N1 – yet the corresponding TRA had not been changed. Engine #4's N1 dropped to a value of around 20%, while the N1 of the other three engines remained at around 97%.

The aircraft's lateral (sideways) acceleration to the right increased, and the magnetic heading also began to increase as the aircraft's course deviated to the right of the runway heading. Input to the right pedal was quickly discontinued, and full left pedal input was applied at 22.36:42 hours. The left pedal was briefly released, for an interval of one second, at 22.36:43 hours, before quickly being reapplied. At the same time, the control wheel was deflected slightly to the left.

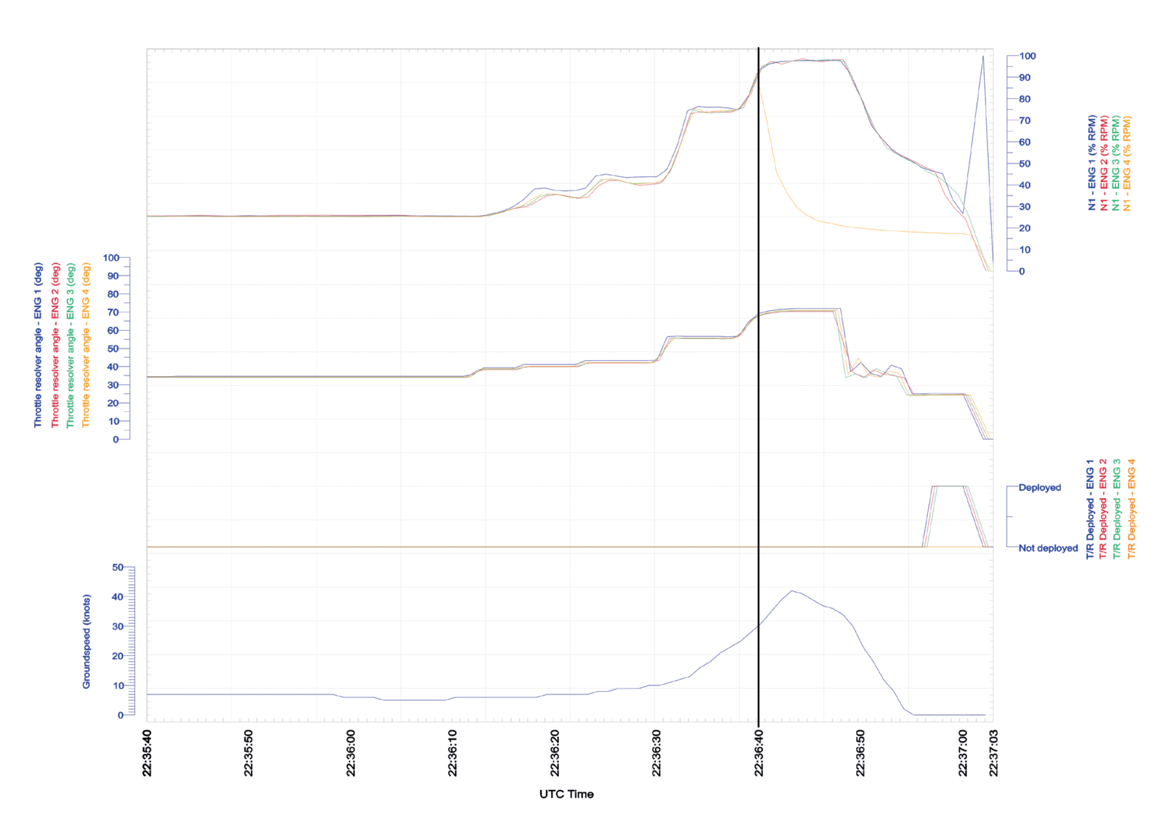


*Figure 2: Plot of FDR data (N1, TRA, T/R, GS). The vertical line indicates the moment at which engine #4's N1 dropped.*

At 22.36:44 hours, the main gear brake torque increased, and the aircraft's longitudinal acceleration began to decrease. Shortly after the initial application of the brake, the brake torques of the right body and wing gear decreased. Higher brake torques on the left wing and body gear, relative to the right, are indicative of differential braking.

The aircraft's ground speed reached a maximum of 42 knots before it began to decrease. At 22.36:46 hours, the control wheel was momentarily deflected around 24 degrees to the left. The thrust levers were reduced to approximately forward idle at 22.36:48 hours. The remaining engines' N1 values began to drop, and the aircraft's longitudinal acceleration decreased. At 22.36:52 hours, at a ground speed of 19 knots, the main gear brake torques dropped to around zero. At 22.36:56 hours as the ground speed reached zero, the thrust levers transitioned to the reverse idle detent, causing the thrust reverser sleeves to transition to the in-transit state. The thrust reverser sleeves were fully deployed around 2 seconds later. At the same time, the deflection of the speed brake handle began to increase. The autothrottle had not been disconnected manually; instead it was automatically disconnected when the thrust reversers were selected.

*Ground Track Analysis*

Using FDR data, the manufacturer prepared a ground track analysis. The results indicate that engine #4's N1 began to decrease 300 feet before the runway displaced threshold. Full left pedal was applied around 80 feet later. The aircraft began to deviate to the right of the runway centreline around 150 feet before reaching the threshold, and the wheel brakes were applied around 100 feet before the threshold was reached. Around 200 feet after crossing the threshold and at a ground speed of 35 knots, the aircraft's centre of gravity (CG) crossed the right edge of the runway. After the aircraft had travelled about another 20 feet (220 feet beyond the threshold), the TRAs were reduced to approximately forward idle. The aircraft's CG departed the paved surface 270 feet beyond the threshold, and the aircraft came to a stop with its CG approximately 380 feet beyond the threshold.

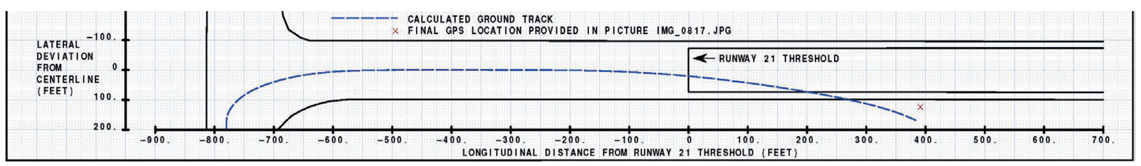


*Figure 3: Ground track analysis. (Source: Boeing)*

### 1.10.2 Cockpit Voice Recorder

The aircraft was equipped with a Honeywell solid-state Cockpit Voice Recorder (CVR). Data from the CVR was successfully downloaded and verified. A transcript of relevant conversations is included in Appendix A to this report.

### 1.10.3 Spectrum analysis

Spectrum analysis of the cockpit area microphone was used to analyse significant sounds, and to determine the exact moment at which the loud bang (that was heard by witnesses) occurred. Following the captain's 'take off' call at 22.36:32 hours (A, Figure 4), the sound of the engines spinning up is visible on the sound spectrum (B). The sound of the engines during the occurrence is visible under line C. At 22.36:36 hours, the captain called 'Set take-off thrust' (D) and the sound of the engines spinning up increases. Around four seconds later a peak can be seen in the sound spectrum, corresponding to the loud bang that was heard (E). The voice of the first officer calling 'abort, abort, abort' is visible at (F), almost immediately followed by the noise of the gear leaving the runway and entering the area of grass (G). (H) is the sound of the TRAs being reduced to idle thrust. The noise made by the deflection of the speed brake handle at around 22.36:55 hours is also visible, at (I).

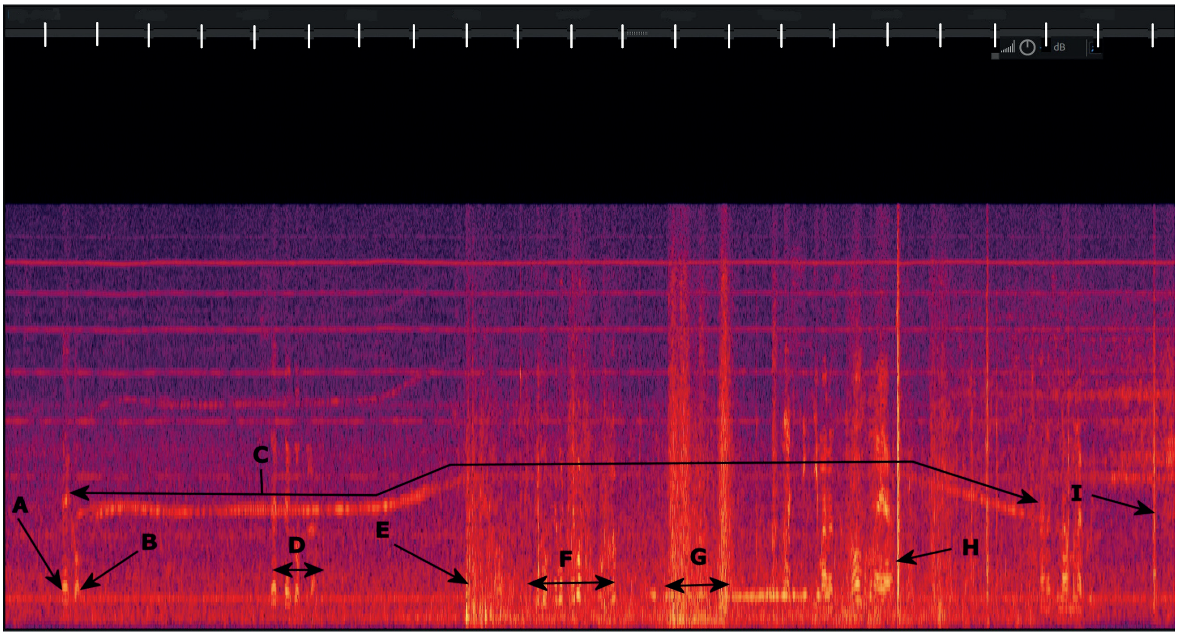


*Figure 4: Spectrum analysis of the occurrence. Each vertical white line corresponds to 1 second.*

## 1.11 Wreckage and impact information

After veering off the runway, the aircraft came to a standstill in the field to the right of Runway 21. All of the main gear's wheels had left deep tracks in the soil. A single track made by the nose gear was clearly visible, as were the double tracks left by each main gear. The left nose wheel had left a curved track, which was wider than the tyre itself. Mud had also been thrown up to the right side of the track. The nose wheels were turned slightly to the left.

*Figure 5: Photographs of wheel tracks in the soft ground.*

The distance from the (displaced) threshold of Runway 21 to the main body gear of TC-ACR was approximately 143 metres. The distance from the entry point of Runway 21 to the aircraft was approximately 363 metres. Skid marks left by the landing gear, deviating to the right, were found on the threshold stripes.

## 1.12 Tests and research

### 1.12.1 Engine examination

After the occurrence, engine #4 was transported to the operator's maintenance facility for repair. Investigators observed the engine High Pressure Compressor (HPC) top case tear down that was carried out when repairing the engine. The records show that this tear down did not include the High Pressure Turbine (HPT) section and the burner section, as borescope inspection had revealed that the engine damage was limited to the HPC.

Some engine components were removed during the tear down. These were the HPC stage 3 and 4 blades, two fan blades, two variable stator vane actuators, two variable bleed valve actuators, three temperature sensors, main fuel pump and hydro mechanical control unit. These components were impounded for examination, as they could have contained clues to the cause of the compressor stall. The descriptions and results of the examinations are summarised in Appendix B.

In addition to the engine top case tear down, the Accessory Gear Box (AGB) oil main chip detector was pulled. This showed evidence of minor contamination. Since the FDR oil parametres appeared to be normal, no engine oil filters or chip detectors were pulled for analysis.

### 1.12.2 Simulator flight

Flight SV916 was reconstructed in a B747-400 full flight simulator. This flight reconstruction (and similar flights using a range of scenarios) was based on FDR data and performance data obtained from flight SV916. Nevertheless, it was not possible to exactly simulate the flight because a reconstruction is an approach to reality and differs with the real circumstances.

These simulator flights revealed that:

- When flight SV916 was repeated under the same conditions and circumstances, the aircraft ended up in almost exactly the same place as the actual aircraft did during the incident flight.
- If there are no indications, it takes a crew several seconds to realise that an engine failure has occurred.
- If loss of thrust occurs on engine #4, this causes the aircraft to immediately yaw to the right.
- Noticing and calling an engine failure helps people to react quickly.
- After a yaw to the right, the initial intuitive response is to apply left rudder pedal input in an attempt to keep the aircraft on the runway.
- It takes about one second for a person to move their feet from the bottom of the pedal (rudder) to the upper part of the pedal, to engage the wheel brakes. This could result in a short interval without any pedal input.
- The seat should be adjusted to the right position, as this is essential for maximum wheel braking.
- If the power of the remaining engines is maintained for more than approximately 4 seconds, the aircraft's tendency to yaw to the right cannot be corrected.

- No alert or warning is given when an engine failure occurs during the take-off roll, in conditions similar to the occurrence in question.

## 1.13 Organizational and management information

### 1.13.1 Certification requirements and Boeing manuals

The certification requirements relating to the controllability of an aircraft on the ground ($V_{MCG}$) are set out in the US Federal Aviation Administration Regulations FAR 25.149, effective February 1, 1965. These regulations define $V_{MCG}$ as follows:

*$V_{MCG}$, the minimum control speed on the ground, is the calibrated airspeed during the take-off run at which, when the critical engine is suddenly made inoperative, it is possible to maintain control of the aircraft using the rudder control alone (without the use of nose-wheel steering) as limited by 150 pounds (667 N) of force, and the lateral control to the extent of keeping the wings level to enable to the take-off to be safely continued using normal piloting skill. (…)*

Given the airport pressure altitude (450 feet) and outside air temperature (5 °C) at the time of the take-off, Boeing calculated that $V_{MCG}$ would have been around 132 knots for a maximum thrust take-off. This number is conservative, as it does not take into account the derated thrust used during this take-off or the effect of nose wheel steering. Also, it assumes that the aircraft is in the critical configuration[3] which may not accurately reflect this take-off.

According to Boeing, to keep control following an engine failure prior to $V_1$ requires the crew to follow the recommended rejected take-off (RTO) procedure. Boeing does not maintain or publish controllability data for an engine failure below $V_1$. Directional control at low speed is accomplished by a combination of nose wheel steering, differential braking, and rudder effectiveness. There is no definitive speed at which the rudder can be called 'effective'; however, the Boeing Flight Crew Training Manual (FCTM) provides the following guidance for initiating take-off roll:

*Initiating Take-off roll (747-400)*
*If cleared for take-off before or while entering the runway, maintain normal taxi speed. When the aircraft is aligned with the runway centre line ensure the nose wheel steering tiller is released and apply take-off thrust by advancing the thrust levers to approximately 1.1 EPR (PW or RR) or 70% N1 (GE). For RR engines, initial EPR settings up to 1.2 are considered acceptable to improve engine operation. Allow the engines to stabilise momentarily then promptly advance the thrust levers to take-off thrust (autothrottle TO/GA). There is no need to stop the aircraft before increasing thrust.*

3 Maximum available take-off power or thrust on the operating engines; the most unfavourable centre of gravity; the aircraft trimmed for take-off and the most unfavourable weight in the range of take-off weights.

*Keep the aircraft on the centreline with rudder pedal steering and rudder. The rudder becomes effective between 40 and 60 knots. Maximum nose wheel steering effectiveness is available when above taxi speeds by using rudder pedal steering.*

*Regardless of which pilot is making the take-off, the captain should keep one hand on the thrust levers until $V_1$ in order to respond quickly to a rejected take-off condition. After $V_1$, the captain's hand should be removed from the thrust levers. The PM should monitor engine instruments and airspeed indications during the take-off roll and announce any abnormalities. The PM should announce passing 80 knots and the PF should verify that his airspeed indicator is in agreement.*

*Rejected Take-off (RTO) Maneuver*
*The RTO maneuver is initiated during the take-off roll to expeditiously stop the airplane on the runway. The PM should closely monitor essential instruments during the take-off roll and immediately announce abnormalities, such as "ENGINE FIRE", "ENGINE FAILURE", or any adverse condition significantly affecting safety of flight. The decision to reject the take-off is the responsibility of the captain, and must be made before $V_1$ speed. If the captain is the PM, he should initiate the RTO and announce the abnormality simultaneously.*
*Note. If the decision is made to reject the take-off, the flight crew should accomplish the rejected take-off non-normal maneuver as described in the Maneuvers Chapter of the QRH. (…)*

### 1.13.2 Operators' manuals

Details of the requirements and regulations pertaining to the aircraft in question are set out in the operators' Boeing 747 FCOM. Part B, Appendix II, the Standard Operating Procedures (SOP) and the Quick Reference Handbook (QRH) are included in the FCOM.

### Standard Operating Procedures

Details of the take-off procedure are set out in sections 2.29.4 and 2.29.6 of the SOP:[4]

*2.29.4 Initiating take-off roll*
*Auto throttle and flight director use is recommended for all take-offs. However, do not follow F/D commands until after lift-off. A rolling take-off is recommended for setting take-off thrust. It expedites the take-off and reduces the risk of foreign object damage or engine surge/stall due to a tailwind or crosswind. Rolling take-offs are accomplished in two ways.*
*If cleared for take-off before or while entering the runway, maintain normal taxi speed. When the airplane is aligned with the runway centreline ensure the nose wheel steering tiller is released and apply take-off thrust by advancing the thrust levers to approximately 1.1 EPR (PW) or 70% N1 (GE).*
*If holding in position on the runway, ensure the nose wheel steering tiller is released, release brakes, then apply take-off thrust.*

4 Take-off procedure as described in SOP is consistent with take-off procedure in FCOM 'Normal procedures'.

*A standing take-off may be accomplished by holding the brakes until the engines are stabilized, ensure the nose wheel steering tiller is released, then release the brakes and promptly advance the thrust levers to take-off thrust (auto throttle TO/GA).*
*Allowing the engines to stabilize provides uniform engine acceleration to take-off thrust and minimizes directional control problems. This is particularly important if crosswinds exist or the runway surface is slippery. The exact initial setting is not as important as setting symmetrical thrust. If thrust is to be set manually, smoothly advance thrust levers toward take-off thrust.*

2.29.6 Take-off procedure

| ***Pilot Flying*** | ***Pilot Monitoring*** |
| --- | --- |
| *The Captain will advance thrust levers to approximately 1.1 EPR (PW) or 70% N1 (GE).<br>Allow engines to stabilise.* | |
| *The Captain will then push TO/GA switch to advance thrust levers to required thrust, or manually advance thrust levers to the required thrust setting.* | |
| *Call "SET Take-off THRUST"* | |
| *Verify that the correct take-off thrust is set.* | |
| | *Monitor the engine instruments throughout take-off. Call out any abnormal indications.<br>Adjust take-off thrust before 80 knots as needed.<br>During strong headwinds, if the thrust levers do not advance to the planned take-off thrusts, manually advance the thrust levers before 80 knots.<br>Call "THRUST SET"* |
| *Captain's hand must be on the THR Levers until $V_1$.* | |
| *Monitor airspeed.<br>Maintain light forward pressure on the control column* | *Monitor airspeed indications and call out any abnormalities.* |
| *Verify 80 knots and call, "CHECKED"* | *Call "80 KNOTS."* |
| *(…)* | *(…)* |

**Quick Reference Handbook**

QRH, Section 1 Non-normal manoeuvres section, provides the following guidance for initiating a rejected take-off:

*Rejected Take-off*

*The captain has the sole responsibility for the decision to reject the take-off. The decision must be made in time to start the rejected take-off manoeuvre by $V_1$. If the decision is to reject the take-off, the captain must clearly announce "REJECT," immediately start the rejected take-off manoeuvre, and assume control of the airplane. If the first officer is making the take-off, the first officer must maintain control of the airplane until the captain makes a positive input to the controls.*

*Prior to 80 knots, the take-off should be rejected for any of the following.*

- *activation of the master caution system*
- *system failure*
- *unusual noise or vibration*
- *tire failure*
- *abnormally slow acceleration*
- *take-off configuration warning*
- *fire or fire warning*
- *engine failure*
- *predictive wind shear warning (as installed)*
- *if the airplane is unsafe or unable to fly*
- *(…)*

*During take-off, the crew member observing the non-normal situation will immediately call it out as clearly as possible.*

| *Captain* | *First Officer* |
|---|---|
| *Without delay.* | *Verify actions as follows.* |
| *Simultaneously close thrust levers, disconnect auto throttle, and apply maximum manual wheel brakes or verify operation of RTO autobrake.*<br><br>*If RTO autobrake selected, monitor system performance and apply manual wheel brakes if AUTOBRAKES message displayed or deceleration not adequate.*<br><br>*Raise speed brake lever.*<br><br>*Apply the maximum amount of reverse thrust on symmetric engines consistent with conditions.*<br><br>*Continue maximum braking until certain the airplane will stop on the runway.*<br><br>*Field length permitting.*<br>*Initiate movement of reverse thrust levers to reach reverse idle detent by taxi speed.*<br><br>*(…)* | *Thrust levers closed.*<br><br>*Auto throttle disconnected.*<br><br>*Maximum brakes applied.*<br><br>*Verify speed brake lever UP and call "SPEEDBRAKES UP." If speed brake lever not UP, call "SPEEDBRAKES NOT UP."*<br><br>*Reverse thrust applied symmetrically. When all REV indications are green, call "REVERSERS NORMAL."*<br><br>*If there is no REV indication(s) or the indication(s) stays amber, call "NO REVERSER ENGINE(S) NUMBER ___" or "NO REVERSERS".*<br><br>*Call out any omitted action items.*<br>*Call out 60 knots.*<br><br>*Communicate reject decision to control tower and cabin as soon as practical.*<br><br>*(…)* |

### 1.13.3 Training

*Simulator training*

The flight crew performed the regular mandatory training and check flights, as put down in Operation Manual Part D (training manual) in a full flight simulator. The flights in question are the Operator Proficiency Check (OPC), License Proficiency Training (LPT) and the License Proficiency Check (LPC). OPCs are flown every six months, while LPTs and LPCs are flown once a year. Details of each of the topics to be taught or checked are laid down in the assessment forms. These must all be covered within a three-year period. Prior to each simulator session, the flight crews are briefed on which items will be taught or checked in that particular session, to give the crews the opportunity to prepare themselves for the flight. Two trainees are trained and checked per simulator session. The topics involved are divided between trainee1 (TR1) and trainee 2 (TR2). The items to be taught and checked with regard to RTOs are set out in the forms, as depicted below.

| | Year 1 | Year 2 | Year 3 |
|---|---|---|---|
| *OPC* | ***TR1.***<br>*Low speed RTO*<br>*Rejected T/O in low visibility*<br>***TR2.***<br>*RTO (contaminated runway)* | ***TR1.***<br>*High/low speed RTO (contaminated runway)*<br>*Rejected T/O in low visibility*<br>***TR2.***<br>*RTO* | ***TR1.***<br>*High/low speed RTO*<br>*Rejected T/O in low visibility*<br>***TR2.***<br>*RTO (wet runway)* |
| *LPT* | ***TR1.***<br>*Low speed RTO*<br>*Engine fail/ before $V_1$ / RTO*<br>***TR2.***<br>*Take off RTO (pilot incapacitation)* | ***TR1.***<br>*Low speed RTO*<br>***TR2.***<br>*RTO before $V_1$* | ***TR1.***<br>*Low/High speed RTO (wet runway)*<br>***TR2.***<br>*RTO (contaminated runway)* |
| *LPC* | ***TR1.***<br>*High/low speed RTO (contaminated runway)*<br>*Briefing, rejected Take off, engine failure in low visibility*<br>***TR2.***<br>*RTO* | ***TR1.***<br>*High/low speed RTO*<br>*Rejected T/O in low visibility, engine failure*<br>***TR2.***<br>*RTO* | ***TR1.***<br>*High/low speed RTO (contaminated runway)*<br>*Rejected T/O in low visibility, engine failure*<br>***TR2.***<br>*RTO* |

*CRM Training*

The flight crew had taken the annual, mandatory Crew Resource Management (CRM) training course. One of the topics covered in 'year two' of this training course, is the "Surprise and Startle" effect. Here, the causes and consequences of this phenomenon are discussed. Various case studies are presented, and recommendations are made on how to prevent this effect.

## 1.14 Additional information

### 1.14.1 Measures taken by the operator

After the occurrence in question, the operator initiated two risk assessments by external parties. One assessment dealt with the runway excursion, while the other focused on the engine failure. The results were presented in an internal report.[5]

Regarding the runway excursion, the following mitigating actions were performed or planned:

- *One extra simulator session has been performed to examine the effectiveness of the RTO procedures at low speed.*
- *A Flight Crew Assessment Board meeting has been held for related crew assessment.*
- *RTO procedures were reviewed*
- *The number of low speed RTO practices in yearly training program will be reviewed depending on simulator RTO examine session with coordination of training department. After this review the training program was extended with an Operator*

5 Operators action-taken report concerning the TC-ACR runway excursion.

*Proficiency Training (OPT). Four RTO procedures are trained during this three-year program, divided between Trainee 1 and Trainee 2.*

- *A safety notice was published to all flight crew to remind RTO procedures.*
- *Internal safety investigation was carried out by SMS department.*

The flight assessment committee planned and carried out an extra simulator session to check current RTO procedures under low speed conditions, and to assess the flight crew involved. This produced the following findings:

- *The time to start RTO especially at wet/contaminated runway is very important.*
- *Flight crews should start the RTO procedure without hesitation when recognizing that the airplane is significantly deviating from the runway centre line.*

Regarding the engine failure, the following mitigating actions were taken:

- *Engine core wash.*
- *Engine high pressure compressor (HPC) borescope inspections.*
- *Other possible mitigation measures will be implemented in accordance with GE's recommendation.*

#### 1.14.2 Information about engine #4

The operator purchased aircraft TC-ACR from another European operator in June 2015. An inspection prior to the delivery flight revealed some damage to parts of the HPC (stage three blades) in the incident engine (#4). After consultation with the engine manufacturer, it was concluded that the damage was within Aircraft Maintenance Manual (AMM) limits, and that there was no objection to the operation of the aircraft.

# 2 INVESTIGATION AND ANALYSIS

## 2.1 General

Aircraft TC-ACR was properly certificated and equipped, in accordance with the requirements. According to the flight and technical logs, no defects or anomalies were encountered during the previous flight. There were no indications that the aircraft had any defects before the start of flight SVA916 to Jeddah. Nor was there any evidence of an existing power plant failure or systems failure before the flight commenced.

The aircraft was loaded in accordance with the loading instruction report. The aircraft's weight and balance were all within limits. Its centre of gravity was almost in the centre of the flight envelope. For this reason, it was concluded that weight and balance played no part in causing this occurrence.

The flight crew consisted of the captain and the first officer. The captain acted as pilot flying and the first officer as pilot monitoring. Both were properly certified, qualified and trained to perform these roles during the flight. Given the number of flight hours and the amount of experience they had accumulated, they can both be deemed to be experienced with the type of aircraft in question, a Boeing 747. This was their first flight after two days leave. Both members of the flight crew stated that they were well rested. Two additional crew members, a technician and a load master had no active role during the flight.

Although Maastricht Aachen Airport normally closes at 22.00 hours, an exemption was granted to allow the aircraft to take-off no later than 23.00 hours. This was because loading operations had not been finished in time. Around 22.19 hours, the crew and the aircraft were ready for departure and the push back onto the taxiway was performed. Although the captain stated in his interview that he felt a little hurried, CVR data indicated that the flight crew had acted calmly prior to the incident.

The incident occurred at night, with overcast skies that blocked any moonlight. This caused one member of the crew to remark about the darkness. All taxiway and runway lights were lit in accordance with the requirements. Given the atmospheric conditions, the setting of the lighting was appropriate. The runway was damp but not slippery. There are no indications that the weather, atmospheric conditions or runway conditions were involved in causing the occurrence.

## 2.2 The flight and the occurrence

Flight preparations and the start of flight SVA916 were all routine. Both pilots performed their tasks as set out in the operator's SOPs. The start-up, the before taxi checklist and the before take-off checklist were all completed before taxi commenced. In view of the distance between the stand and the runway, this was understandable. In fact, this enabled the pilots to concentrate fully on the task of taxiing to the runway in darkness.

The crew received take-off clearance while approaching Runway 21. This enabled them to commence a rolling take-off, maintaining a ground speed of approximately 5 kts during the right turn to line up on the runway. At 22.36:34 hours, the captain advanced the thrust levers to approximately 70%. As thrust increased to the selected take-off power, a minor difference developed between engine #4 and the remaining engines. As a result, some pedal steering inputs were required to keep the aircraft aligned with the runway centreline. At this time, engine #4 (and, to a lesser extent, engine #3) was producing noticeably more thrust than the other engines. The steering inputs were to the right, as the difference in thrust was causing the aircraft to veer to the left.

When the engines had stabilised at 70% N1 the captain pressed the TO/GA switches, thus engaging the autothrottle. The captain's call-outs and actions, and those of the first officer, were all in accordance with the SOPs. However, the first officer's saying 'Set thrust', followed by the captain's 'Take off' are not mentioned in SOPs or checklists. No explanation could be given for these calls. The whole sequence of the crew's actions was in keeping with a routine flight, involving nothing out of the ordinary.

During the start of the take-off roll, the tasks were divided up as prescribed in the manuals; the captain was looking outside and keeping the aircraft in the middle of the runway, while the first officer monitored the instruments. Four seconds after the autothrottle was engaged, at a ground speed of 30 kts, a loud bang was heard and the N1 of engine #4 dropped to around 20%. In his interview, the captain stated that he did not hear the bang because he was the only one who was wearing an active noise cancelling headset over both ears and because the noise originated from the right side of the aircraft. The first officer had only one of his ears covered by his headset, while neither the technician nor the load master were wearing headsets. The fact that only these three individuals heard the bang confirms the assumption that the captain did not hear the noise because it was muted by his headset.

Unable to hear the loud bang, the captain could not understand why the aircraft was suddenly yawing to the right-hand side of the runway. This triggered the normal response of trying to counteract this yaw by steering to the left, by means of nose wheel rudder pedal steering. As the captain was still applying the right rudder pedal, it took some time before he could switch to the left rudder pedal once the right yawing occurred. The captain also stated that he used the nose wheel steering tiller to steer the aircraft to the left.

### 2.2.1 Application of the tiller

The tiller is designed to steer the aircraft on the ground, by turning the nose wheel. The tiller can be used to turn the nose wheel up to 70 degrees left and right, when making tight turns. The use of differential thrust is limited to very tight turns, for instance when an aircraft has to make a 180-degree turn on the runway. In all other situations, the tiller and – to a lesser extent – differential braking is used. If high turning angles are used, taxi speed should be limited to around 10 kts, to avoid nose wheel skidding.

By design, the tiller and the rudder pedals both use the same actuators on the nose wheel. The tiller inputs override control inputs by the rudder pedals. Steering input from the rudder pedals is limited. They are unable to turn the nose wheel by more than 7 degrees. This prevents nose wheel skidding during the take-off roll, when maximum input is being applied to the rudder pedals. As the rudder control surface is controlled by the rudder pedals, maximum control input is necessary when operating the aircraft just above $V_{MCG}$ in case an outboard engine failure should occur.

According to the manuals, use of the tiller during a take-off roll should be avoided. The tiller should, therefore, be released by the pilot. If the nose wheel is turned more than 7 degrees, this increases the risk of nose wheel skidding, which makes steering less effective. Therefore, the rudder pedals should be used to steer the aircraft down the centreline of the runway. At the start of the take-off roll, the captain should normally have one hand on the control column and the other on the throttles. The FCTM of Boeing and the SOPs of the operator direct the captain to keep hold of the throttles at all times until $V_1$ is reached, after which point a safe reject manoeuvre can no longer be guaranteed. After $V_1$, both hands are normally positioned on the control column.

### 2.2.2 Flight control inputs during the incident

Following push-back and engine start, both the before taxi checklist and the before take-off checklist were completed before the aircraft taxied to the runway. During taxiing, the captain had to perform two 90-degree turns to align the aircraft with the runway centreline. As he taxied the aircraft, he used his left hand to operate the tiller while using his right hand to increase the thrust slightly to achieve a taxi speed of around 5 kts (consistent with the FCTM's recommended taxi speed for 90 degree turns).

As he aligned the aircraft with the runway centreline, the captain increased thrust to perform a rolling take-off. Thrust is set using the right hand, so the captain's right hand was holding the thrust levers. At that time, he was operating the tiller with his left hand. This suggests that he was not holding the control column. This was confirmed by FDR data, which showed that zero force was being exerted on the captain's control column at that point. The thrust difference between the engines during spin-up was such that the N1 of engine #4 was higher than the N1 of the other three engines. This resulted in a yaw to the left. As a result, the captain had to make corrections with the rudder pedals, steering to the right during the initial phase of the take-off.

The captain then felt the aircraft yaw suddenly to the right. Unaware of the cause, he tried to arrest this movement by using nose wheel steering inputs. As stated, he used both pedal and tiller nose wheel steering. However, tiller inputs override rudder pedal inputs.

When it became clear that nose wheel steering was not sufficient, he applied brake pressure. This occurred three seconds after the beginning of the event, as shown by an increase in the main gear brake torques. FDR data showed that, initially, both the right-hand and left-hand main gear brakes were engaged. Shortly thereafter, braking of the right-hand gear decreased, which is indicative of differential braking. Although the aircraft had initially been heading a little to the left, it subsequently experienced an increasing deviation to the right. As take-off power was still engaged, the combined effect of tiller nose wheel steering and differential braking was insufficient to counteract the yaw to the right.

According to FDR data a control wheel input (steering to the left) was recorded shortly after the engine failure occurred. Thus, while the captain was holding the tiller with his left hand, he had most probably moved his right hand from the thrust levers to the control wheel. The captain was of the opinion that he had retarded the thrust levers almost immediately after noticing the deviation. However both FDR data and CVR data showed that the thrust levers were retarded to idle approximately eight seconds after the N1 drop of engine #4. This means that asymmetric thrust was acting on the aircraft for eight seconds.

The captain stated that he had tried to steer the aircraft to the left, using the tiller to keep the aircraft on the runway, while the first officer stated that he did not operate any controls. Thus, it was concluded that the captain's left hand remained on the tiller until the aircraft had come to a full stop at its final resting place. Tiller inputs are not recorded on the FDR, so additional data was analysed for evidence of the use of tiller nose wheel steering. This analysis is based on three strands of evidence.

1. Tyre marks in the soft ground

The tyre marks associated with each individual landing gear strut were carefully examined. The nose wheel tracks in the grass were of particular interest. It was concluded that the shape and size of the nose wheel track in the grass indicated a nose wheel steering angle ranging from around 26 degrees to around 36 degrees to the left. This track ran from the point where the nose wheel had left the runway surface to the aircraft's final resting place. Although the calculated steering angles (based on the nose wheel track) are merely an indication, they clearly exceed the maximum steering angle of 7 degrees that can be achieved by pedal steering. It is, therefore, very likely that this was caused by inputs to the tiller nose wheel steering system.


*Figure 6: Analysis of the nose wheel track. The red line indicates the orientation of the aircraft; the yellow line indicates the angle of the nose wheel.*

2. Damage to the aircraft

Boeing's analyses of the forces exerted on the nose wheel, which were responsible for the damage to the front section of the aircraft, revealed that the deceleration force on the nose wheel was consistent with a nose wheel steering angle of more than 7 degrees. According to the manufacturer, all ground loads act on the well structure (doghouse) of the nose landing gear. Although the actual loading involved in this case was difficult to quantify, based on the buckle pattern in the skin (45-degree pattern in the buckles), it appears that there was a significant amount of compression-shear-related loading. This is consistent with a left turn, due to the operation of the tiller, which would force the doghouse loads into the supporting structure (including the skins), as compression.

3. FDR

FDR analysis revealed that left control wheel input was recorded from the moment the engine failure occurred until the moment the throttles were finally retarded to idle. There was an interval of 1 second between control column release and retardation of the throttles. This is consistent with the time required for the captain to move his right hand from the control column to the throttles. Accordingly, it is likely that the captain was not holding the control column with his left hand, but that he was instead using this hand to operate the tiller. It can be concluded that the captain was holding and using the tiller throughout the event, making control steering inputs that exceeded 7 degrees of nose wheel steering.

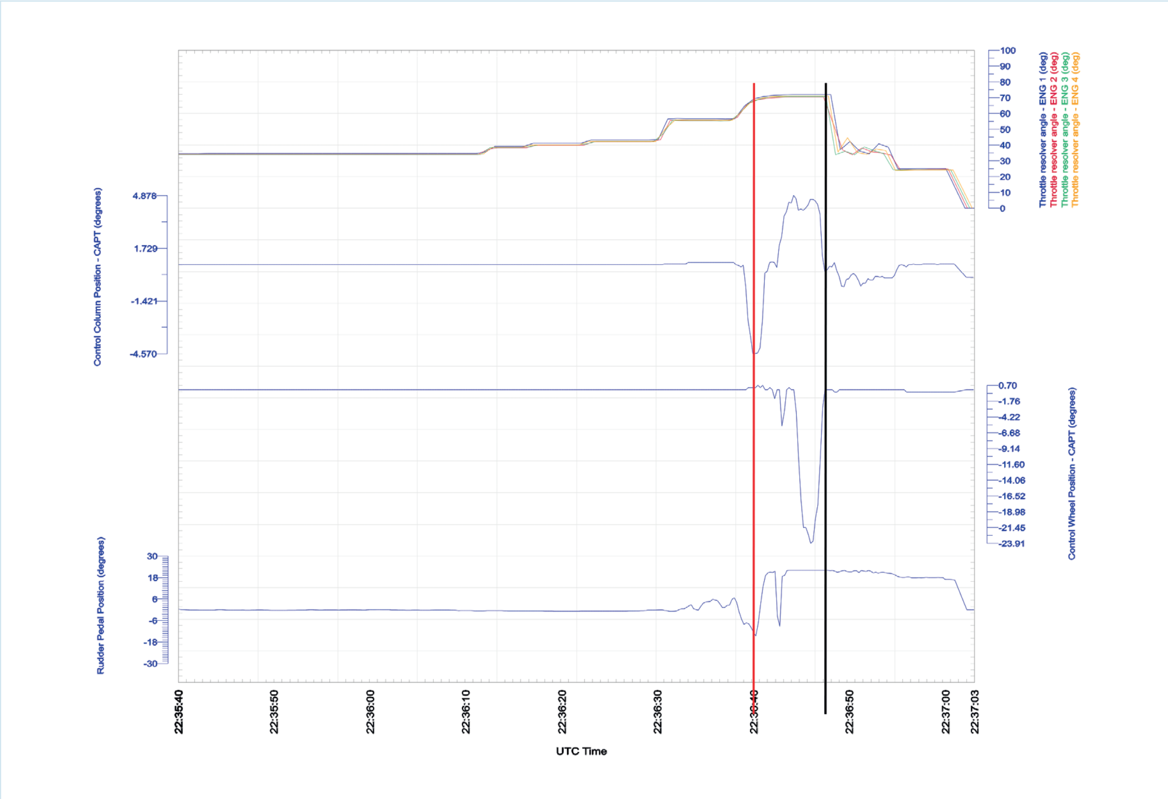


*Figure 7: Plot of FDR data (TRA, control column, control wheel, rudder pedal). The red vertical line indicates the point at which the N1 of engine #4 dropped; the black vertical line indicates the moment at which the throttles were retarded.*

### 2.2.3 Rejected take-off procedure (RTO)

During the take-off procedure, the first officer's task is to monitor the engine instruments, call out any abnormal indications, and adjust take-off thrust as necessary until the aircraft reaches a speed of 80 kts. Initially, all engine instrument readings were normal. Thus his attention was focused on the air speed indicator, as he was required to call out the speed when the aircraft reached 80 kts. Immediately after the aircraft yawed to the right, the first evidence that an anomaly had occurred was the loud bang that he heard. No caution or warning was audible or visible on the EICAS, but the combination of the bang and the yaw indicated to him that the situation was very serious. That was probably why – almost immediately after these events – he called "off, abort, abort, abort", in an effort to get the captain to abort the take-off. The interval between the bang and his abort call was a little more than one second. Partly because there was no caution or warning, he did not notice the drop in engine #4's N1. As a consequence, he did not call out 'engine failure' as a reason for rejecting the take-off (the procedure specified in the manuals). Because the first officer did not announce the reason for the RTO, the captain did not know what had prompted the first officer's abort call.

Despite the call to abort the take-off, the captain initially tried to keep the aircraft on the runway by a combination of steering and braking. The thrust levers were retarded to forward idle about eight seconds after the N1 of engine #4 dropped, and around six seconds after the first officer's call to abort. The selection of reverse thrust resulted in automatic disconnection of the autothrottle and extension of the speed brakes. At that point, the aircraft had already veered off the runway to the right and had rolled onto the grass. The thrust levers were not closed immediately, so they were still at the take-off power setting when the aircraft veered off the runway and rolled onto the soft ground. By the time the thrust levers were moved to forward idle, the speed of the aircraft had already dropped almost to zero, due to the combined effects of the applied brakes and of the drag created by the soft ground.

Information obtained from the FDR, the CVR and the pilot interviews showed that the standard rejected take-off procedure had not been followed. Although the first officer was aware of the need to reject the take-off, the captain's actions were consistent with an attempt to keep the aircraft on the runway by means of rudder pedal, braking, control column and tiller inputs. It can be concluded that, during the event, the captain had been using his left hand to operate the tiller and that he had moved his right hand from the throttles to the control wheel. This means that the captain was no longer holding the throttles, in contravention of the take-off procedure.

As the throttles were not retarded, a runway excursion became inevitable. This is because, if there is an outboard engine failure at low speed, while the remaining engines are at take-off thrust, it is impossible to keep the aircraft on the runway.

## 2.3 Asymmetric thrust

The drop in engine #4's N1 resulted in an asymmetric thrust. Engines #1 and #2 on the left side of the aircraft were producing more thrust than engines #3 and #4 on the right side, which resulted in a yaw to the right. The effect of a loss of thrust on engine #4 seizing was amplified by the fact that this engine is on the outside of the wing, which resulted in the loss of a large moment on the right side. The outside engines (#1 and #4) are defined as critical engines: "*the engine whose failure would most adversely affect the performance or handling qualities of an airplane.*"[6]

The purpose of the RTO procedure described in the manuals is to keep an aircraft under control after an engine failure prior to $V_1$. Directional control at low speed is accomplished by a combination of nose wheel steering, differential braking and rudder effectiveness. The rudder only becomes effective at speeds of between 40 and 60 kts. Thus, it was not effective in this case, as the aircraft's ground speed was around 30 kts when the N1 of engine #4 dropped. This incident has shown that, when three engines are producing take-off power and an outboard engine loses power, nose wheel steering and differential braking are not sufficient to keep the aircraft in the middle of the runway. To counteract the effects of asymmetric thrust at low speed, immediate action is required. As stated in the manuals, a crew member who observes an anomalous situation of this kind must immediately call this out as clearly as possible, stating the nature of the anomaly. According to the manuals the appropriate procedure for neutralizing asymmetric thrust is

6 Boeing 747 Flight Crew Training Manual.

to simultaneously close the thrust levers, disconnect the autothrottle, raise the speed brake lever, apply maximum wheel brakes and apply maximum reverse thrust on symmetric engines.

As shown during test flights in the full flight simulator, unless appropriate action is taken within about four seconds, it is impossible to keep the aircraft on the runway after an outboard engine failure under the same (derated) conditions. In the case of a full rated take-off, the available response time would be even shorter.

Certification requirements regarding the controllability of an aircraft on the ground when a critical engine becomes inoperative, $V_{MCG}$, only apply to speeds at which it is possible to maintain control of the aircraft using the rudder control alone. In the case of TC-ACR, this speed would have been around 132 kts. This highlights the fact that there are no certification requirements for cases in which a critical engine becomes inoperative at low speed.

## 2.4 Engine failure

It was the loss of thrust on engine #4 that led to this incident. The cause of the loss of thrust was not investigated in depth, as contained single engine failures do not automatically meet the criteria for an accident or serious incident. However, the engine was subsequently disassembled for repair by means of a top case tear down, which presented the opportunity to examine some components.

High Exhaust Gas Temperature (EGT), a low stabilised core engine speed of around 79% and falling, plus the drop in engine #4's N1 (fan speed) following a loud bang, are all strong evidence of a compressor stall.

The laboratory analysis found no animal cell material or DNA of animal origin. Based on this finding and on the absence of other foreign material, it can be concluded that the compressor stall was not caused by Foreign Object Damage (bird, litter).

Compressor stalls can sometimes occur in strong and gusty crosswind conditions. However, taking into account the prevailing wind conditions at EHBK (250/03, varying from 210 to 330) during take-off, the weather can be ruled out as a causative factor of a compressor stall.

In the high-pressure compressor (HPC), there was evidence of damage to some of the compressor blades in stages 3 and 4. A metallurgical investigation demonstrated that this damage had existed prior to the event. It seems that the damage to some stage three blades in the HPC had previously been assessed by the engine manufacturer, who had concluded that this damage was within acceptable limits. Hence, there was no objection to the operation of the aircraft with this engine (General Electric, CF6-80 series, s/n 706-509) installed at position #4. Therefore, as the HPC damage was considered to be minor, this cannot solely account for the compressor stall. After all, the engine was operated several flight without any problems.

Many parts of engine #4 that are related to the engine control loop showed anomalies, with respect to their condition or performance. No fault messages were shown in earlier flights, however the absence of messages does not exclude these anomalies. The Dutch Safety Board took the decision to refrain from any further analysis of the compressor stall and has no opinion on maintenance because this has not been investigated. Nevertheless, the technical state of the engine may well have been a factor here, given the overall condition of the components related to the engine control loop and the condition of the fuel pump.

## 2.5 Noise cancelling headsets

The captain, as the only member of the crew, had covered both ears with a noise cancelling headset. The American FAA drew attention to the use of these types of headsets twice. In Info Bulletin 07001 of 5 January 2007 and in Special Airworthiness Information bulletin CE-16-08 of 20 November 2015 the FAA advises operators and pilots of concerns with the use of noise cancelling headsets. When wearing these headsets, the pilot may be unaware of environmental sounds and audible warning annunciations in the cockpit that do not come through the intercom system. Noise cancelling headsets are most effective over a narrow frequency range, but the specific frequencies may vary by make and model. Therefore, it is difficult to assess any effects the headsets may have on discerning environmental sounds such as:

- Vital communications between flight crew members or flight attendants, other than those attainable through interphone operations;
- Abnormal mechanical noises or abnormal engine sounds;
- Audible alarms other than those discernible by electronic means;
- Vibrations or wind noises;
- Other aircraft during ground operations.

Therefore operators and crew members of aircraft are advised to evaluate their use of noise cancelling headsets.

## 2.6 The startle effect

Following the loss of thrust on engine #4, the crew did not respond as they had been trained to and their actions were not in accordance with the RTO procedures described in the manuals. This behaviour could be explained by a phenomenon known as a 'startle effect'. In aviation, a startle effect can be defined as an uncontrollable, automatic reflex that is elicited by exposure to a sudden, intense event that violates a pilot's expectations.[7]

7 FAA Advisory Circular 120-111 dated 4/14/15 - Upset Prevention and Recovery Training.

The startle effect has been described extensively in the Skybrary article about this subject.[8] According to this article: *"The startle effect includes both the physical and mental responses to a sudden unexpected stimulus. While the physical responses are automatic and virtually instantaneous, the mental responses - the conscious processing and evaluation of the sensory information - can be much slower. In fact, the ability to process the sensory information - to evaluate the situation and take appropriate action - can be seriously impaired or even overwhelmed by the intense physiological responses.*

*In addition to the temporary physiological changes which follow a high intensity stimulus, studies have determined that, following a startling stimulus such as a loud noise, basic motor response performance can be disrupted for as much as 3 seconds and performance of more complex motor tasks may impacted for up to 10 seconds.*

*The time that it takes to recover in a cognitive sense, after a startle event, must also be considered. Startle has been found to impair information processing performance on mundane tasks, such as the continuous solving of basic arithmetic problems, for 30 to 60 seconds after the event occurrence. The duration of the performance degradation increases as the task becomes more complex. Thus, the startle effect disrupts cognitive processing and can negatively influence an individual's decision making and problem-solving abilities.*

*As concluded by Martin, Murray and Bates in their paper The Effects of Startle on Pilots During Critical Events,[9] the reliability of modern aircraft is part of the context in which inappropriate actions are sometimes taken after an unexpected event:*

*"… one of the common themes as aircraft become more reliable is that pilots are surprised or startled by some event and as a result have either taken no action or alternatively taken the wrong action, which has created an undesired aircraft state, or in some cases, an accident. This surprise or startle is largely due to the enduring reliability of the aircraft and the aviation system, which has unwittingly created a conditioned expectation of normalcy among today's pilots. The problem then is the level of expectation of novel or critical events is so low that the level of surprise or startle which pilots encounter during such events is higher than they would perhaps have had some decades ago when things went routinely wrong."*

*On the flight deck, pilots may be exposed to a variety of stimuli that have the potential to elicit the startle reflex and response. Bird strike, aircraft upset, simultaneous failure of multiple engines and visual stimuli, such as sudden illumination by lasers, have all resulted in incidents where pilots have been startled or even disoriented. In aviation, the immediate impact of the startle reflex may induce a brief period of disorientation as well as short term psychomotor impairment which may well lead to task interruptions and/or a brief period of confusion. Should this happen, a period of time will be required for reorientation and task resumption. While performance after a startle event can be*

8 https://www.skybrary.aero/index.php/Startle_Effect.

9 Martin, W., Murray, P. and Bates, P. (2012). The Effects of Startle on Pilots During Critical Events: A Case Study Analysis. www98.griffith.edu.au.

*affected to the detriment of safety of flight, the greater concern stems from what the crew did, or did not do, during the conditioned startle response itself. It is here that decision making can be most significantly impaired, especially higher-order functions necessary for making judgments about complex flight tasks."*

This investigation revealed that the flight crew's actions corresponded to some symptoms of the startle effect, as described above. In the interval until the aircraft had come to a complete stop, no mention was made of engine failure and the captain's RTO actions were not monitored, nor was there any communication between the members of the flight crew. Such actions are consistent with the impact of a startle event. Someone asked '*what happened?*' after the aircraft had stopped, indicating that their actions were prompted by surprise.

People experiencing a sudden, intense event can show target fixation. They may also experience communication difficulties and be unable to follow standard procedures. This was the case here. The captain's actions were focused on keeping the aircraft on the runway, the target he was fixating on. With regard to the thrust levers in particular, the procedures he had been taught (which are also described in the manuals) seemed to have been forced into the background. This lasted until the aircraft had come to a complete stop in soft soil. The first officer became aware that an anomaly had occurred when he heard the loud bang, which was immediately followed by the aircraft yawing to the right. His initial reaction to these events was to call out 'Off, abort, abort, abort', although he did not immediately state his reasons for doing so. In addition, the standard RTO procedures were not followed. This is consistent with the 'startle effect'.

The flight crew (like all of this operator's flight crews) underwent flying training and check flights three times a year. Within a period of three years, all of the topics listed on the assessment form have to be taught and checked. Each session includes one type of RTO, e.g. standard RTO, plus high speed and low speed RTOs on contaminated runways. Each year, they are trained in low speed RTOs following an engine failure. Before each simulator session, the flight crews are briefed on the items to be taught or checked in that particular session. This is to give them the opportunity to prepare themselves for the flight. As a result, the crew members are not surprised when an engine failure occurs at low speed during take-off in that simulator session. Knowing what to expect, they are well prepared for the actions that need to be taken. Any startle effects encountered in this setting will be very limited, compared to those that crews experience when exposed to 'real life' events.

# 3 FINDINGS AND CONCLUSION

## 3.1 Findings

The aircraft TC-ACR was properly certified, equipped and maintained, in accordance with requirements. There was no evidence of an existing power plant or systems failure prior to the commencement of the flight.

The aircraft's weight and balance were within limits.

The take-off performance calculations were in accordance with the procedures.

The captain and the first officer were properly certified and qualified for the roles they were to perform during the flight.

There is no evidence that the weather, atmospheric conditions or runway conditions contributed to this occurrence.

When take-off power was selected, a compressor stall occurred in engine #4. At this point the aircraft had a ground speed of around 30 kts and had not yet reached maximum take-off power.

The loss of thrust resulted in engine #4's N1 dropping to around 20%, thereby producing asymmetric thrust.

The pilot monitoring did not notice the loss of thrust on engine #4, but he was aware of the seriousness of the situation and urged the captain to abort the take-off.

Because the pilot monitoring did not announce the loss of thrust, the pilot flying continued to be unaware of the reason for the pilot monitoring's call. This omission was partly due to the lack of any caution or warning.

The asymmetric thrust caused the aircraft to suddenly yaw to the right.

The pilot flying had no information and was unaware of the cause of the deviation. As a result, he was surprised and he reacted intuitively. The use of a noise cancelling headset could have played a role.

In an attempt to correct the deviation to the right, the pilot flying used nose wheel tiller and rudder pedal steering, as well as differential braking.

The thrust levers were not immediately retarded to idle. Nor were other standard procedures followed. Such delays and not following trained procedures have been associated with the phenomenon known as the 'startle effect', experienced by both the pilot flying and the pilot monitoring.

Throughout the event, the pilot flying used his left hand to operate the tiller while moving his right hand from the throttles to the control wheel, releasing the thrust levers in the process.

Because he did not keep his hands on the thrust levers, asymmetric take-off power was engaged for around eight seconds.

As a result of this continued asymmetric thrust, it became impossible to control the aircraft and the runway excursion became inevitable.

The rejected take-off procedure must be initiated immediately if sudden asymmetric thrust occurs during the take-off roll at low speed.

Each year, crews are trained in rejected take offs at low speed following an engine failure. However, no 'startle effects' will occur during these training sessions as the flight crews know what to expect.

There are no certification requirements for situations in which a critical engine becomes inoperative during take-off below $V_{MCG}$.

The engine loss of thrust was due to a compressor stall. The cause of the compressor stall remains unknown, although Foreign Object Damage (FOD) and wind turbulence have been excluded. However, the technical state of the engine as found might have contributed to this event.

## 3.2 Conclusion

The runway excursion was caused by the pilot's inability to maintain directional control under the conditions of prolonged asymmetric thrust that resulted from the loss of thrust on engine #4 at low speed. The loss of engine thrust was caused by a compressor stall.

*Contributing factors*

The thrust levers were not retarded immediately after the loss of thrust. Such delays and not following trained procedures have been associated with the phenomenon known as the 'startle effect'.

During training courses in flight simulators, the lessons learned from unexpected situations, such as engine failures, are quite limited as the crews know what to expect.

# APPENDIX A

## TRANSCRIPT

| From | FDR time (UTC) | Message |
|---|---|---|
| Capt | 22.33:22 | Before taxi checklist |
| Capt | 22.33:42 | Three up to down, three up to down, rudder, full left, full right *(check of flight controls)* |
| FO | 22.34:02 | Before taxi checklist, anti-ice |
| Capt | 22.34:04 | Anti-ice off |
| FO | 22.34:05 | Recall |
| Capt | 22.34:06 | Check |
| FO | 22.34:08 | Auto brake |
| Capt | 22.34:10 | RTO |
| FO | 22.34:11 | Flight controls |
| Capt | 22.34:12 | Checked |
| FO | 22.34:13 | Ground equipment |
| Capt | 22.34:14 | Clear |
| FO | 22.34:15 | Before taxi checklist completed. |
| FO | 22.34:16 | It is very dark |
| Capt | 22.34:18 | Ok, OLNO 2Bravo, 160, Runway 21, to initial 60, transition 3000, before take-off checklist |
| FO | 22.34:29 | Before take-off checklist, flaps |
| Capt | 22.34:30 | 20 |
| FO | 22.34:31 | Take off briefing |
| Capt | 22.34:32 | Review |
| FO | 22.34:33 | Upper deck |
| Capt | 22.34:34 | Secure |
| FO | 22.34:35 | Before take-off checklist completed |

| From | FDR time (UTC) | Message |
|---|---|---|
| Capt | 22.34:36 | Ok, ready for taxi |
| FO | 22.34:41 | Maastricht, Saudia 916 ready for taxi |
| Capt | 22.34:44 | Ready |
| ATC | 22.34:46 | … 916, to line up and wait Runway 21 |
| FO | 22.34:51 | Line up and wait Runway 21, Saudia 916 |
| Capt | 22.34:54 | Clear on the left |
| FO | 22.34:56 | Clear on the right |
| Capt | 22.35:02 | Only line up, switch light on |
| Capt | 22.35:06 | Line up items |
| FO | 22.35:20 | Weather left, terrain right |
| ATC | 22.35:35 | Saudia 916, Runway 21 , the wind 260 4 knots, you are cleared take off |
| FO | 22.35:40 | Cleared take off, Runway 21, Saudia 916 |
| Synthetic voice | 22.35:41 | Approaching 21 |
| Capt | 22.35:45 | Have a safe flight |
| FO | 22.35:47 | Indeed |
| Capt | 22.35:49 | Is the radiofrequency stand by or not? |
| FO | 22.35:51 | We did already |
| Capt | 22.35:56 | Have a good flight |
| FO | 22.35:58 | Have a nice flight |
| Capt | 22.36:14 | Do we switch to departure frequency at 2000 feet ? |
| Synthetic voice | 22.36:26 | On Runway 21 |
| FO | 22.36:31 | Set thrust |
| Capt | 22.36:32 | Take off |
|  | 22.36:33 | Sound of engines spinning-up |
| Capt | 22.36:36 | Set take-off thrust |
|  | 22.36:40 | Loud noise (bang) |
| FO | 22.36:41 | Off, abort, abort, abort |
|  | 22.36:44 | Sound of wheels hitting something |

| From | FDR time (UTC) | Message |
|---|---|---|
| Capt | 22.36:46 | (…) What happened…. |
| | 22.36:48 | Sound of engines spinning-down |
| Capt | 22.37:00 | Switch off the engines |
| ATC | 22.37:08 | Saudia 916 |
| FO | 22.37:11 | Ah, we are out of runway, Saudia 916 |
| ATC | 22.37:13 | Roger |
| ATC | 22.38:50 | Saudia 916, can you give us some information what happened |
| Capt | 22.39:00 | We really don't have an idea, after brakes off, then start take off, unable to .. aircraft on the runway, what really happened, I don't know |
| ATC | 22.39:16 | Roger, that is copied |

# APPENDIX B

## ENGINE EXAMINATION

*Examination of HPC blades*

A borescope inspection carried out on the platform after the occurrence revealed damage to stage 3 and 4 compressor blades in the HPC. Two HPC stage 3 blades (numbers 6 and 7) and two HPC stage 4 blades (numbers 19 and 30) were sent for laboratory examination.

The laboratory examination report indicated that there was no evidence of any relevant impact damage to the stage 3 blades of the HPC. However, it did find that the leading edge tip of blade #6 was missing, due to a fatigue fracture. The high cycle fatigue crack had originated in the tip area and had propagated to the leading edge. While there was no trace of impact damage, there was evidence of tip rub and burr, which may have caused the fatigue in question.

The two HPC stage 4 blades showed damage to their leading edges, both due to impacts originating from the concave side of the airfoil. In blade #30 traces of Ti64 were found in the tip curl, a different alloy from the HPC stage 4 base metal (Ti442).

HPC stages 1, 2 and 3 are made of Ti64, so a fragment of material from these locations could have struck blade #30. In this case, the missing piece of blade #6 could have impacted blade #30. The dented surfaces in the leading edge and the fatigue fracture surface in all of these blades were severely eroded. This could be a result of the position and orientation of these surfaces with respect to the airflow. Moreover, dust trails were found in the dents. It can, therefore, be assumed that this damage occurred many cycles before the engine stall in question. During the previous borescope inspection of engine #4 (on 12 October 2017) the combustor chamber and HPT stages 1 and 2 were inspected.

In summary: the blades that were examined showed no evidence of severe damage. Tip rub resulted in the loss of the leading edge tip of blade #6. Furthermore, all the fractured and dented surfaces were severely eroded, and dust trails were found. Thus, it was concluded that this damage had been caused several cycles before the stall in question, and that such damage solely was not the cause of the compressor stall.

*Fan blade examination*

During the top case engine tear down, the engine fan inlet and fan blades were subjected to a black-light inspection. Spots of material that may have been organic in nature were found on two fan blades from engine #4, which were then removed for additional laboratory assessment. That examination found no traces of animal cell material or animal DNA on the fan blades.

*VSV and VBV actuator examination*

Prior to disassembly, the actuators that drive the Variable Stator Vanes (VSVs) and variable bypass valves (VBVs) were tested. This was because a malfunction of these components could potentially cause a compressor stall.

The VSV actuators showed no obvious damage and were able to travel freely between the 'up' and 'down' positions. These actuators were sent to the engine manufacturer for further testing. A further examination revealed worn rod end bearings of both actuators and worn body bearings of one actuator, which meant that it was not possible to set the stroke of the actuators.

The VBV actuator check showed that the valve was able to travel from the VBV's fully open position to its fully closed position. Its operation was also found to be satisfactory. Additional leakage tests conducted by the manufacturer revealed various leaks of one actuator.

*Temperature sensors*

Two T12 engine inlet temperature sensors and one T25 compressor inlet temperature sensor were sent to the manufacturer for tests and examination. Two temperature sensors (T12 and T25) were tested. The sensors met the performance requirements but they failed the visual inspection criteria for re-installation, due to corrosion.

*Fuel pump*

The fuel gear pump was sent to the manufacturer for tests and examination. This fuel pump failed the test and visual inspection, as it was found to have cavitation damage with some bronzing. According to the manufacturer, the pump hardware showed signs that it may have been run without fuel. The fuel pump was scrapped.

*Brake system control unit (note: not part of engine but is included here for convenience)*

Data from the Brake System Control Unit (BSCU) was downloaded to determine whether any system faults had been reported. Following the downloading and examination of this data, it was found that no faults or anomalies had been recorded.

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