An Additional Approach to Establishing the State of Operation of a Turbofan Engine During an Aircraft Accident

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Abstract

Understanding the damage to the engines involved in an aircraft accident can provide insight into their state of operation at the time of impact. In the majority of investigations, an evaluation is performed at the accident scene by assessing the condition of the blades in the compressor and turbine sections of the engine. This classic approach to determining the state of operation of an engine has been utilized successfully for many years and has been widely taught as a fundamental investigative tool to generations of aircraft accident investigators. The fundamental premise being that if the blades are bent against the direction of rotation, the rotors were rotating and if the rotors were rotating the engines were operating. A recent accident involving a large commercial airplane, however, highlighted that this type of assessment has limitations. The on-scene evaluation of one of the engines proved to be misleading and the evaluation was changed following additional assessment. This paper will discuss the method of that assessment. Secondly, the paper will also describe what information the engines yielded about the aircraft ground impact sequence, given an absence of the majority of the aircraft.

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Background of accident

A twin-engine commercial passenger jet was reported to have crashed in a remote area with thick vegetation similar to what would be found on the edges of a jungle. A team of investigators was dispatched to the scene to begin the investigative process.

The team arrived on-scene and observed that significant looting of the wreckage had already occurred. The majority of the aircraft had been removed including the Flight Data Recorder that was later recovered, but was not in a useful condition. All that remained were the two engines midway along, and on opposite sides of, the wreckage path.

Based on observations both on the ground and from aerial surveys, it was determined that the aircraft came in at a shallow angle [see Figure 1] and at a significant bank angle with the right wing down [see Figure 2].

The detailed examination of the accident site identified both engines. Figure 3 is of the engine found on the left (1) hand side of the wreckage path while Figure 4 is of the engine found on the right hand side of the wreckage path. On-scene examination of both engines identified significant differences in the distress to the fan blades from one engine to the other with the engine on the right hand side of the wreckage path exhibiting very little distress to the fan blades and the engine on the left having just the opposite appearance. Further examination of the engine on the right hand side of the wreckage path identified the same lack of distress to the rear stage turbine blades.

The on-scene investigation concluded with a recommendation that the engines be examined further to understand the differences in their observed levels of distress.

Basics of jet engine construction

In simplified terms, a jet engine inducts air into an intake, compresses the air in compressor stages, mixes this compressed air with fuel and then ignites that mixture in the diffuser/combustor section, and then exhausts the combustion gases through turbine stages that extract work to drive the compressor and other ancillary systems. In a typical turbofan engine the forward most compression stage(s) is/are called the fan stage(s).

The mechanical construction of the compressor and turbine sections involves the close proximity, usually in an alternating pattern, of hardware that rotates and hardware that remains stationary. The diffuser/combustor section, that does not contain any rotating hardware, separates the compressor and turbine sections from one another. Surrounding all of the static and rotating hardware are cases that provide the positioning of the rotating hardware relative to the static hardware. Figure 5 is a cross section of an exemplar turbofan engine.

It is this construction, specifically the close proximity of rotating to stationary hardware, which provides the accident investigator with a potentially valuable source of information regarding the state of rotation of the rotating parts of the engine during the impact sequence.

Classic approach to understanding accident engines

Due to the dynamics of an accident sequence, it is typical for an aircraft engine to impact the surroundings as opposed to coming to rest in graceful or soft manner. The dissipation of the energies involved in an aircraft wreckage result in the generation of significant forces that can distort and compromise the structures involved, including the engines. This could mean ground impact, water impact, or impact with any other obstructions (e.g. trees, buildings, etc.) that were encountered along the wreckage path.

Relating back to the discussion on the basics of jet engine construction, the distortion of the engine structure itself due to the impact forces brings the rotating and stationary hardware into contact with each other. This contact leaves signatures on that hardware that can then be interpreted by the accident investigator.

As engine cases distort and intrude into the rotating blades of the compressor and/or turbine sections, the blade distress is directly related to the rotational speed of the engine rotors at the time of the incursion. As a general rule, the higher the level of damage, the faster the rotating hardware was rotating. Said differently, the faster a rotating part is rotating, the more energy there is that needs to be dissipated. This energy dissipation takes the form of hardware deformation and distress and thus can provide a measure as to the state of operation of the engine at the time of impact.

Taking this concept and putting it to practical application it is worthwhile to examine a couple of examples.

Figure 6 is an example of a fan rotor from an engine that was not rotating/windmilling (2) (i.e. an unpowered engine) at the time of impact. Note how the majority of the blades exhibit very little, if any deformation. They are straight and full length. Note also how a sector of the blades is buckled. This is interpreted as meaning that the rotor was not rotating at the time of its impact allowing only the blades that were in the area of the deformed case to become deformed.

Figure 7 is an example of a compressor rotor from an engine that was rotating at high speed at the time of impact. The blade rows from this example have been liberated completely, folded over against the direction of rotation, or fractured off leaving only stubs of blades still attached to the underlying disk. The explanation for this is that the rotor, with blades attached, was rotating fast enough that all of the blades rotated past/into the deformed part of the engine case. Since all of the blades encountered this intrusion of the case into the rotor they all became distressed in a similar fashion.

Levels of distress between the extremes depicted in Figures 6 and 7 can also be used to infer state of rotation. Figure 8 is an example where ~75% of the blades are fractured but the remainder are full length and straight/undeformed. The energy level of this impact was somewhere between no rotation of the engine and high-speed rotation. In this example the engine was rotating, but at the low (relative to high power take-off) rotational speed of idle.

Utilizing the concepts described above to evaluate the accident initially described, one could come to a potential scenario where, at the time of their impacts, the engine located on the left side of the wreckage path was operating, while the engine on the right hand side of the wreckage path was not.

With the information available from the on-scene portion of the investigation, and the lack of other definitive data, a decision was made to disassemble and examine the engines.

Detailed examination and analysis of the accident engines

During the examination of the engines, serial numbers permanently marked on certain engine components were used in conjunction with the operator's records to determine the installed positions of the engines on the accident aircraft. This evaluation identified the engine on the left hand side of the wreckage path as being the No. 2 engine (installed on the right hand side of the aircraft) and the engine on the right hand side of the wreckage path as being the No. 1 engine (installed on the left hand side of the aircraft).

<u>Examination of the No. 2 engine</u>

Examination of the No. 2 engine identified 1st stage fan blades that were both fractured and bent against the direction of engine rotation. Additionally, the 2nd stage fan blades that were observable were all bent against their direction of rotation. Splintered wood was also observed between the blades in both the 1st and 2nd stage fans. Figure 9 is representative of the condition of the fan stages of this engine.

Circumferential scoring was observed on the aft side of the intermediate case.

The forward side of the 6th stage bleed cavity was caked with organic vegetation debris consisting of dirt and finely chopped wood particles.

In general, it was observed that the blades in the High Pressure Compressor (HPC) were either fractured or exhibited damage against the direction of rotor rotation. This damage consisted of blade bending, leading edge and trailing edge breakouts and smearing, and tip curls. The distress within a given rotating stage was consistent around the entire circumference. Figure 10 is a picture of a typical compressor rotor from this engine.

All gaspath surfaces within the HPC were coated with organic vegetation that consisted of dirt and finely chopped wood particles.

The domes of the burner cans exhibited a deposited coating of organic vegetation that consisted of dirt and finely chopped wood particles. Figure 11 depicts this debris.

The blades in the High Pressure Turbine (HPT) and Low Pressure Turbine (LPT) stages of the engine were observed to be in-place and intact. No blades fractures in the turbine were identified.

There were no findings during the examination of the No. 2 engine that indicated a pre-accident malfunction of the engine.

Examination of the No. 1 engine

Examination of the No. 1 engine did not identify any significant distress to the blades of the 1^{st} or 2^{nd} stage fans. All of these blades were observed to be intact and straight with no significant deformation or distress. Figure 12 depicts the observed condition of the fan from the No. 1 engine on-scene.

All of the primary gaspath surfaces in the HPC were coated with organic vegetation debris that consisted of dirt and finely chopped wood particles.

All of the HPC blades were observed to be in-place, intact, and straight. Figure 13 is a typical compressor rotor from this engine.

The Combustion Chamber Outer Case was noted to be dented inwards, consistent with an external impact, from 6:00-9:30 o'clock (3).

The domes of the burner cans exhibited a significant deposit/caking of organic vegetation consisting of dirt and finely chopped wood particles.

Organic vegetation consisting of a mixture of dirt and finely chopped wood particles was deposited on the largest diameters along the entire lengths of the individual burner cans. Figure 14 depicts the deposited debris on the burner cans.

The inside of the burner cans exhibited a thin coating of organic vegetation debris consisting of dirt and finely chopped wood particles.

A significant amount of organic vegetation debris, consisting of finely chopped wood particles, was caked around the holes for the burner cans in the combustion chamber support assembly. Figure 15 depicts this debris.

The blades in the HPT and LPT stages of the engine were observed to be in-place and intact. No blade fractures in the turbines were identified.

There were no findings during the examination of the No. 1 engine that indicated a pre-accident malfunction of the engine.

Analysis of No.2 engine findings

The condition of the fan and compressor stage blades in the No. 2 engine were consistent with the rotors rotating at the time the engine received its impacts. Furthermore, the distress to the fan and compressor blades as compared to the lack of distress to the turbine blades indicated that the forward portions of the engine were where the initial engine impacts occurred which in turn arrested the rotation of the engine rotors.

The circumferential scoring observed on the aft side of the intermediate case was consistent with the HPC still rotating at the time the relative axial positioning of the high pressure rotor to the intermediate case was lost. This was consistent with the engine rotors rotating while the cases were being deformed during the impact sequence.

With no findings of pre-impact failure of the No. 2 engine, and signs of rotation of the engine rotors at the time of impact of the No. 2 engine, the conclusion was drawn that this engine was operating during the portion of the accident sequence when the engine impacted the trees/ground.

Analysis of No. 1 engine findings

The No. 1 engine did not exhibit the blade distress that is typically associated with an engine that is rotating at the time of its impacts during the accident sequence. The blades also did not exhibit a localized area of distress, such as a quadrant of buckled blades, which could be explained by an engine that was not rotating at the time of its impacts. Both of these points could be explained by the condition of the engine cases. The only significant deformation noted to the engine cases was to the Combustion Chamber Outer Case, which does not have any blades in close proximity to it to leave indications as to the state of rotor rotation.

With the lack of blade damage to help establish the state of rotor rotation, the investigation focused on understanding the organic debris deposits in the engine. As noted, the debris contained finely chopped wood that was found deep within the engine past all of the compression stages. It was determined that for the wood to have been chopped in the manner it was, something had to have done work on it, specifically the compressor blades. For this to have occurred, the engine rotors had to have been rotating at the time it encountered the trees. It is not feasible to have branches rammed into the front of the engine and still get chopped in the same manner as observed unless that engine was operating under power at the time it encountered the trees.

Substantiating further that the engine was operating was the manner in which the debris was deposited on the raised surfaces of the burner cans. The debris was deposited in a manner that was consistent with it being entrained in airflow and then being caught on the high points of the surfaces that the airflow encountered. Again, this pointed to the engine operating and pumping air at the time the wood was being ingested.

Finally, as was noted previously, there were some findings of finely chopped wood in the No. 2 engine, although significantly less than what was found in the No. 1 engine. A qualitative comparison of the wood from both engines assessed that the wood in each engine had been chopped to the same degree. With the mechanical damage to the blades of the No. 2 engine establishing that it was rotating at the time it sustained its impacts, the finely chopped wood in this engine was determined to be characteristic of what wood would look like when ingested by an engine that was operating and thus provided further substantiation that the No. 1 engine was operating at the time it encountered trees.

Understanding of the differences in engine conditions

The determination of the engine installed positions, based on the operator's records and positive identification of serialized components in the engines, provided further insight into the conditions of the engines and the aircraft impact sequence. The relative positions of the engines at the accident site were consistent with the engines crossing the wreckage path during the accident sequence. In other words the engine installed on the left hand side of the aircraft (No. 1 engine) ended up on the right hand side of the wreckage path, while the No. 2 engine came to rest on the left hand side of the wreckage path.

The understanding that the engines had crossed the wreckage path was important in further understanding the differences in the observed levels of mechanical damage within each of the engines. Recalling that the orientation of the aircraft was right wing down as the aircraft entered the trees at the accident site, it was recognized that the No. 1 engine traveled through the treetops, and their associated thin construction, while the No. 2 engine encountered the more robust tree trunks that were closer to the ground.

The tree trunks provided a more substantial threat to the No. 2 engine in addition to that engine encountering the ground earlier than the No. 1 engine during the accident sequence. By contrast, the No. 1 engine traveled through the thin treetops ingesting vegetation as it went along for a relatively longer period of time before it came in contact with the ground. This time allowed for the No. 1 engine to ingest the thin debris at the tops of the trees, chop that debris, and deposit it deep within the engine without the engine sustaining the mechanical damage typically associated with an engine that is determined to have been operating at the time it was impacted during the accident sequence.

Finally, the dented Combustion Chamber Outer Case indicated a significant impact to the No. 1 engine in an area where no blades were present. Thus, there was no incursion of static hardware into rotating hardware within the engine to provide an indication of engine rotation, or lack thereof, during the accident sequence.

On-scene observation combined with the examination of the engines helped to explain how the engines came to rest on opposite sides of the wreckage path from their installed locations on the aircraft. With the right wing down orientation of the aircraft, it was determined that the No. 2 engine impacted the ground and separated from the aircraft early in the accident sequence. After separation of this engine, it continued to travel in a straight trajectory as the remainder of the aircraft turned to the right and passed the engine. This allowed the No. 2 engine to come to rest on the left hand side of the wreckage path. The No. 1 engine separated later in time with the aircraft turning right and came to rest on the right hand side completing the process of the engines crossing the wreckage path.

Conclusions

The initial on-scene work during this accident investigation identified differences in the level of mechanical damage between the No. 1 and No. 2 engines. This difference in mechanical damage suggested the possibility that the No. 1 engine was not operating at the time of the accident. A disassembly and examination of both engines was accomplished to understand the conditions of the engines.

The examinations confirmed, via the traditional technique of evaluating the mechanical damage to the compressor blades, that the No. 2 engine, located on the left hand side of the wreckage path, was operating at the time of its impacts. Furthermore, finely chopped wood deposited within this engine was identified during the examination.

The examination of the No. 1 engine, located on the right hand side of the wreckage path, did not identify the mechanical damage signature typical of an engine that was operating during the accident sequence. The examination of this engine did not identify impacts or distress to the static structure of the engine that would produce blade distress that could be used to establish the state of rotation of this engine. Detailed examination of this engine did identify finely chopped wood deposited in the burner area of the engine. A qualitative assessment of this wood, including a comparison to the wood found in the opposite engine, led to the assessment that the engine was operating at the time it encountered trees at the accident site.

The positive identification of the installed positions of the engines combined with the survey of the accident scene further enhanced the understanding of the condition of the engines. With the understanding that the engines had crossed the wreckage path during the accident sequence and the observation that the aircraft entered the trees in a right wing down attitude, an understanding was reached that the No. 1 engine (exhibiting no blade damage) entered the tree tops and ingested relatively thin vegetation while the No. 2 engine encountered heavier vegetation and impacted the ground earlier in the accident sequence. The No. 1 engine thus had time to process and accumulate debris before coming to rest at the accident site. The manner in which the debris in the engine was processed was consistent with having work (i.e. chopping) performed on it that was consistent with an engine that was operating at the time it encountered trees at the accident site.

This accident investigation highlighted that the traditional method of understanding the state of operation of an engine during an accident sequence can be misleading. An engine that was initially suspect of not rotating at the time of its impacts was later determined to have been operating through a further examination. This examination utilized the finding of chopped wood within the engine to establish that is was operating at the time it encountered trees at the accident site. Furthermore, the documentation of the accident scene and positions of the engines was instrumental in understanding why the two engines exhibited different appearances and aided in the explanation of the damage observed.

(1) When describing the wreckage path, left and right are referenced looking in the direction of flight.
(2) Windmilling is a condition of unpowered free rotation/spinning.
(3) Clock references are looking at the engine from the rear with 12:00 o'clock being at Top Dead Center (TDC).

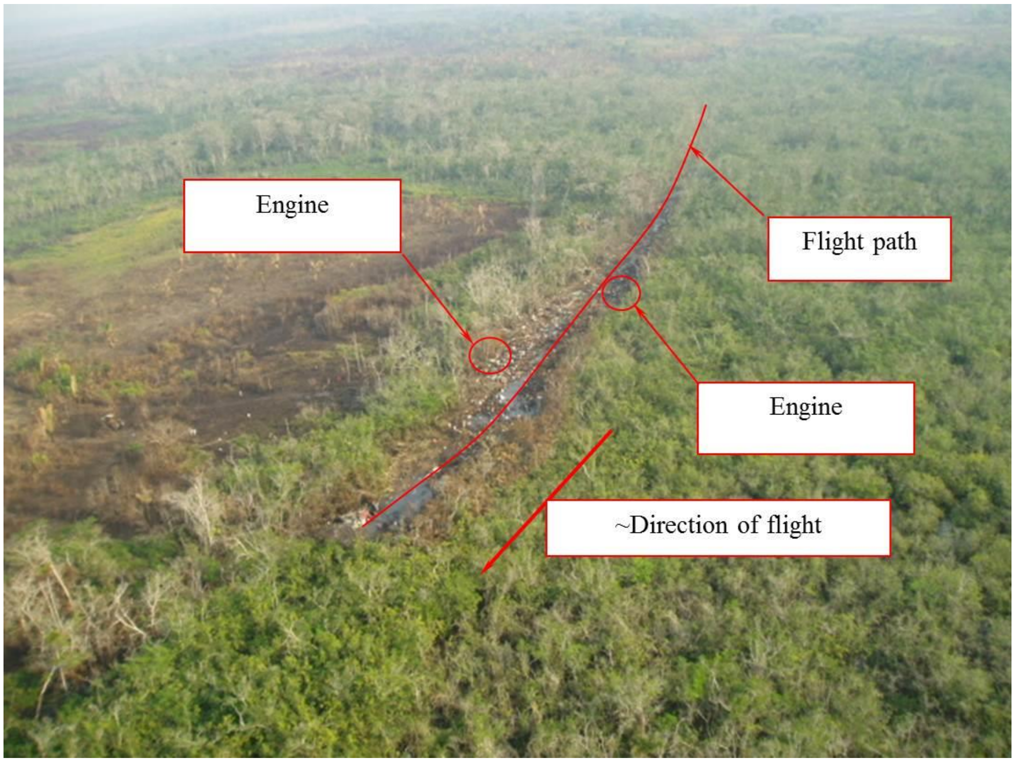

Figure 1: Aerial view of accident site depicting a shallow angle of impact (Photo Credit: CIAA Peru)

Figure 2: View looking against the direction of flight depicting aircraft bank angle with right wing down

Figure 3: Engine on left hand side of wreckage path (Photo Credit: CIAA Peru)

Figure 4: Engine on right hand side of wreckage path (Photo Credit: CIAA Peru)

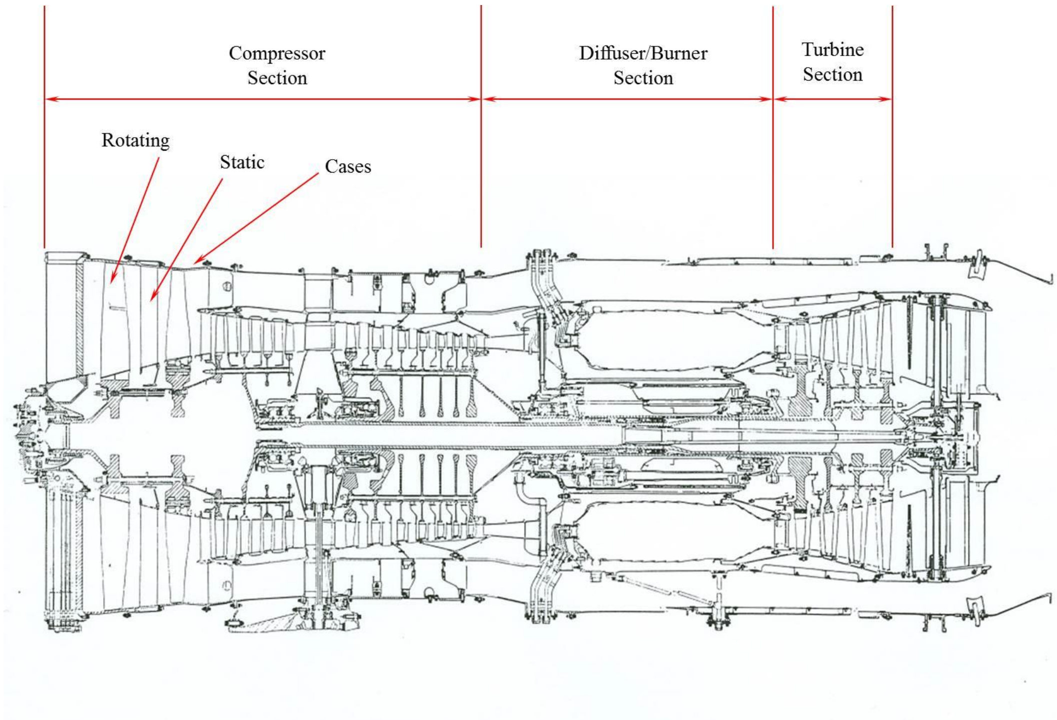

Figure 5: Cross-section of an exemplar turbofan engine

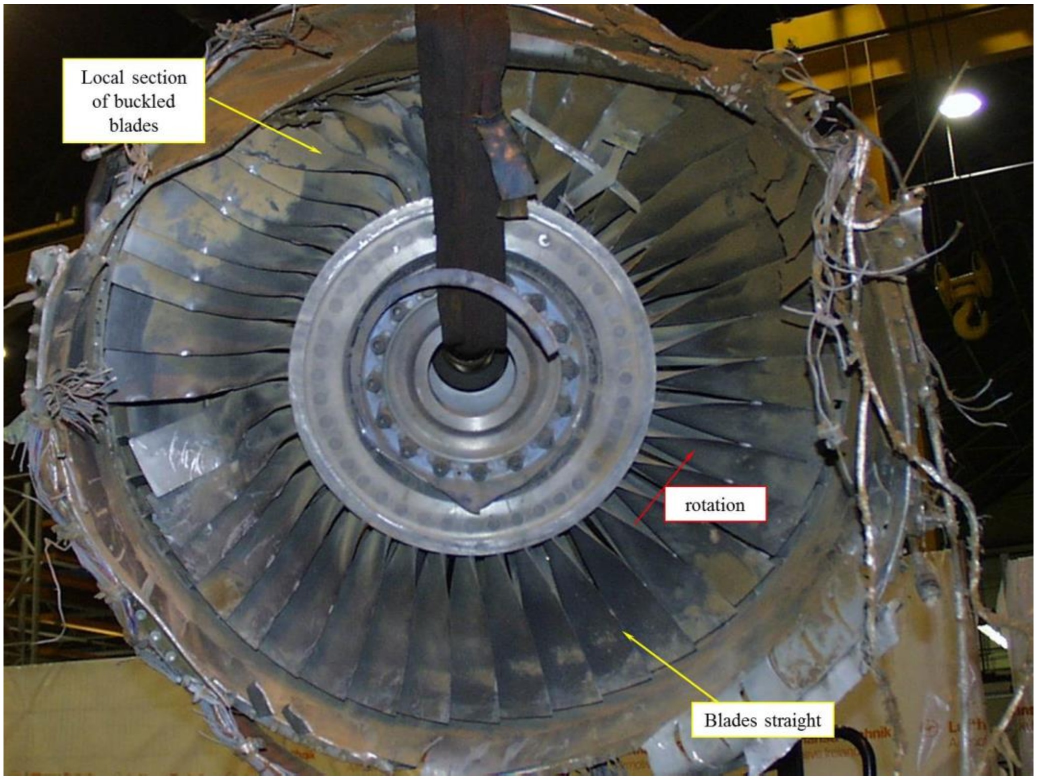

Figure 6: Historical example of blade damage that occurs at impact with little (windmilling) or no rotor rotational speed

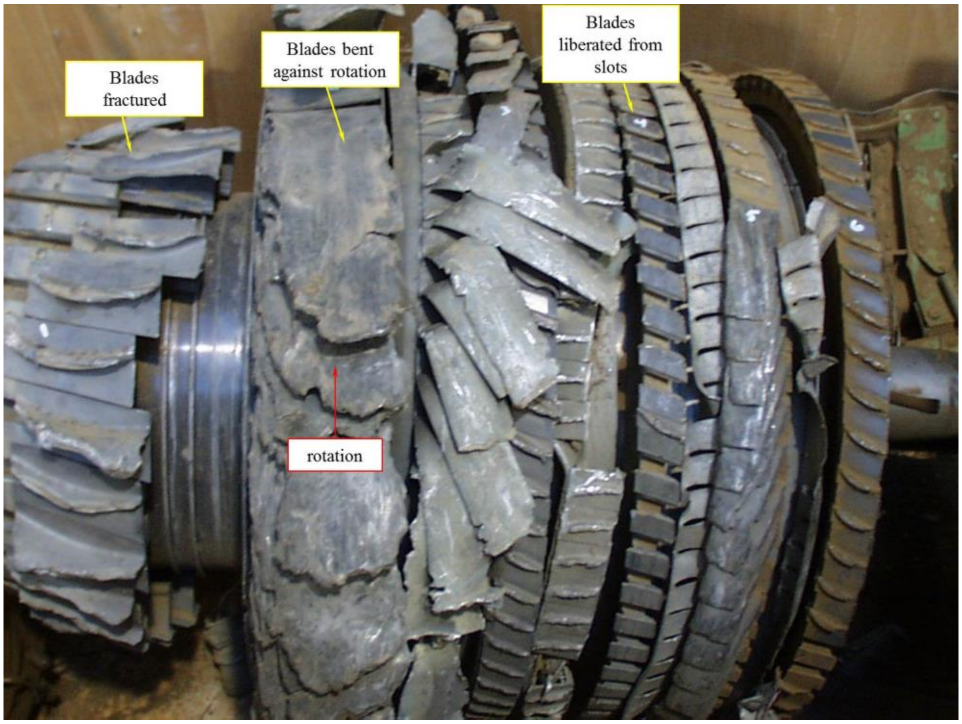

Figure 7: Historical example of blade damage that occurs at impact with the rotor at a high rotational speed

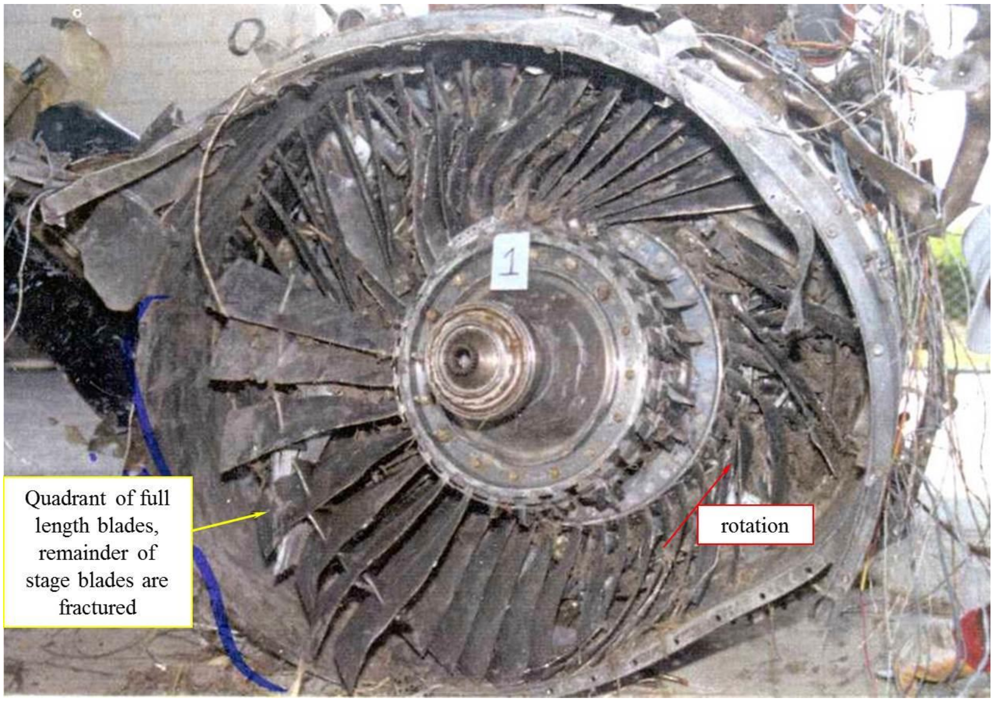

Figure 8: Historical example of blade damage that occurs with rotor at low (~idle) rotational speed

Figure 9: Representative fan stage damage for the No. 2 engine (Photo Credit: CIAA Peru)

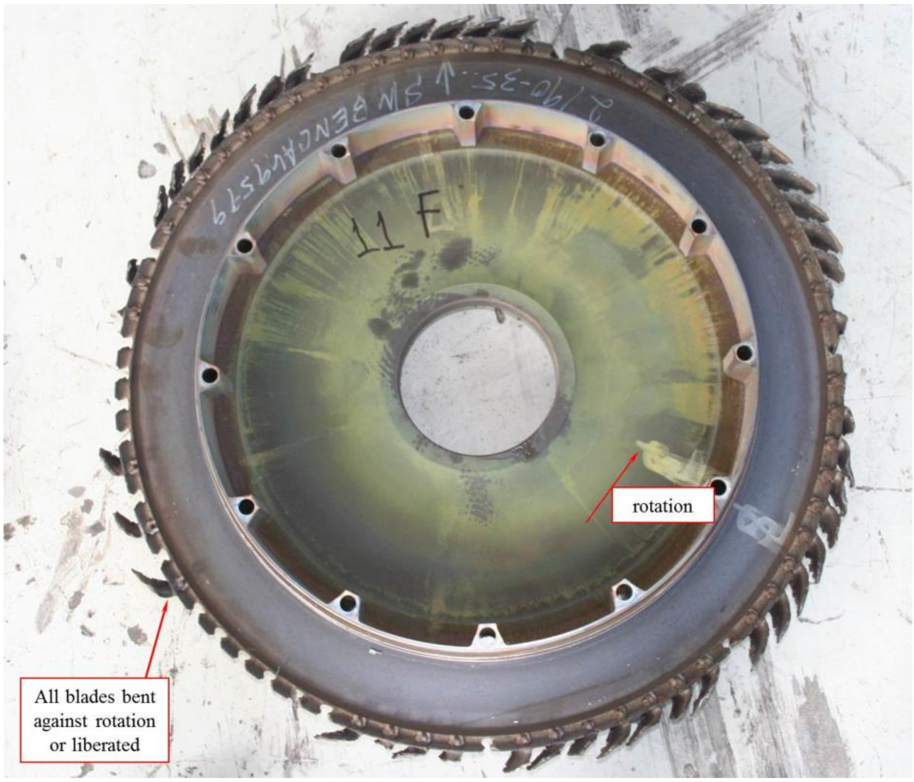

Figure 10: Typical compressor rotor from the No. 2 engine

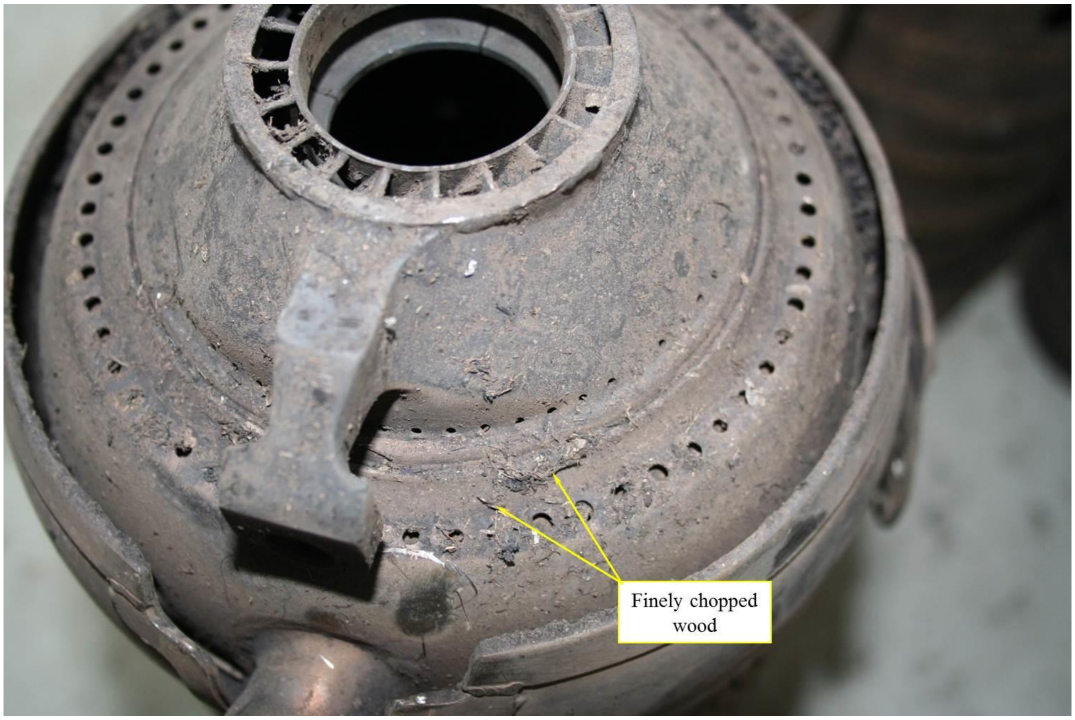

Figure 11: Typical No. 2 engine burner dome with organic deposits included finely chopped wood fragments

Figure 12: No. 1 engine fan stage as observed at the accident site

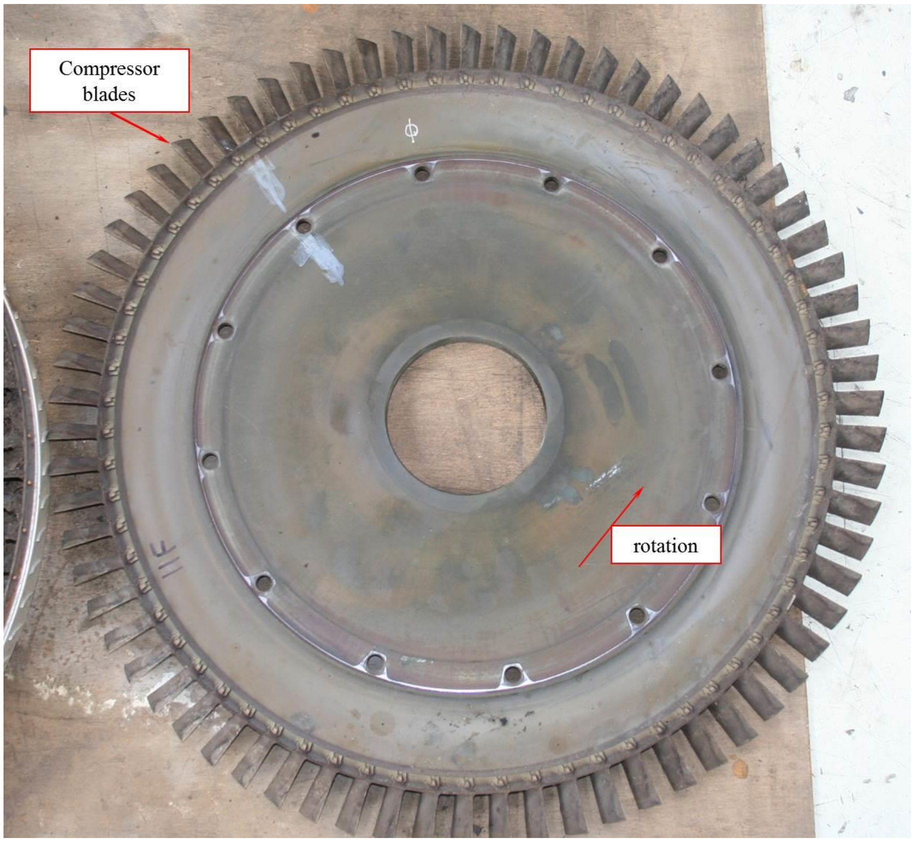

Figure 13: Typical compressor rotor from the No. 1 engine

Figure 14: No. 1 engine burner cans exhibited deposited debris on high spots (largest diameters)

Figure 15: Deposited debris, including finely chopped wood fragments, deposited on combustion chamber support assembly