Aerodynamic, Flight Mechanical and Flight Technical Aspects of the EL AL 1862 Accident Investigation

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Abstract
On October 4, 1992 El Al flight 1862, a Boeing 747 freighter aircraft crashed into a residential area in a suburb of Amsterdam due to loss of control following the separation of two engines from the wing. This paper addresses the investigation from the time of engine separation to the final loss of control. A number of tools and techniques used during the investigation are described. The background of a number of recommendations of the official accident investigation is explained. Answers are discussed on the four main questions raised during the investigation. The aerodynamic effects contributing to the final loss of control are explained. The issue of direction of turn in case of engine failure is re-examined, as well as the consequences of the choice between controllability and performance, when approaching the ground rapidly.

1. Introduction

On October 4, 1992 an El Al Boeing 747-258F crashed into an apartment block in the Bijlmermeer, Amsterdam. The findings of the accident investigation were published in Aircraft Accident Report 92-11 by the Netherlands Aviation Safety Board. This paper summarizes a presentation given for the Netherlands Association of Aeronautical Engineers early 1995. In that presentation a number of findings and recommendations of the accident investigation were amplified from an aerodynamic, flight technical and flight mechanical point of view. It should be realised, that the whole accident investigation did comprise many more aspects, that are not covered in this paper.
The analysis of the events following separation of the engines 3 and 4 until the final loss of control of the aircraft is discussed.
As stated in the Netherlands law on the investigation of aviation incidents and accidents the main objective of an accident investigation is to learn lessons to avoid future accidents. This is also the main aim of this paper.

2. The initial investigation

The so-called operational subgroup of the investigation team was initially confronted with a number of perplexing questions, when the flight data recorder data became available.

These questions were:

- Why did the aircraft fly in apparent control for 8 more minutes after engine separation before the final loss of control?

Note: It took the team about 8 months before a final understanding of the course of events was reached.

- Why was a seemingly inappropriate landing runway chosen by the flight crew for landing?
- What is the best direction of turn with two engines failed on one side?
- And in a later stage of the investigation an additional question arose: why was power applied just before the loss of control?

The main emphasis during the investigation was to answer these questions as it was expected from the start of the investigation, that lessons could be learned for the entire aviation community.

3. Tools used in the investigation

During the investigation many different tools were used. The data from the DFDR (Digital Flight Data Recorder) were essential. These data were initially used by the Netherlands National Aerospace Laboratory NLR to generate a video animation of the flight path and motions of the aircraft. Further detailed analysis of

all recorded parameters was performed. From Air Traffic Control (ATC) radar plots a reconstruction was performed of the path of the aircraft related to the earth.
Unfortunately the Cockpit Voice Recorder (CVR) was not recovered, so no direct information on what transpired in the cockpit was available. However some limited information could be derived from an ATC tape, that records all aircraft-ground communications via an open microphone in the cockpit. Another important source of information were findings from the wreckage.

The main source of information was the DFDR. This system fortunately contained many parameters (81) with a sampling rate depending on parameter from 8 per second to once each 4 seconds. However the tape was heavily damaged during impact and quite sophisticated techniques had to be used in order to obtain useable data. For details of data reconstruction from the tape, where e.g. bit dump techniques had to be used, the reader is referred to the official aircraft accident report. Even with this amount of effort there were many data drop outs, in particular near the end of the flight. In order to obtain meaningful time histories all data were inspected by hand and reconstructed using good piloting and engineering judgement. Two examples are given, viz. the Engine Pressure Ratio (EPR) and the rudder deflection time histories. The raw unaltered data obtained from the DFDR tape and the information available after data reconstruction (filtered data) is given in the following figures.

Fig. 1 Unfiltered EPR data from DFDR

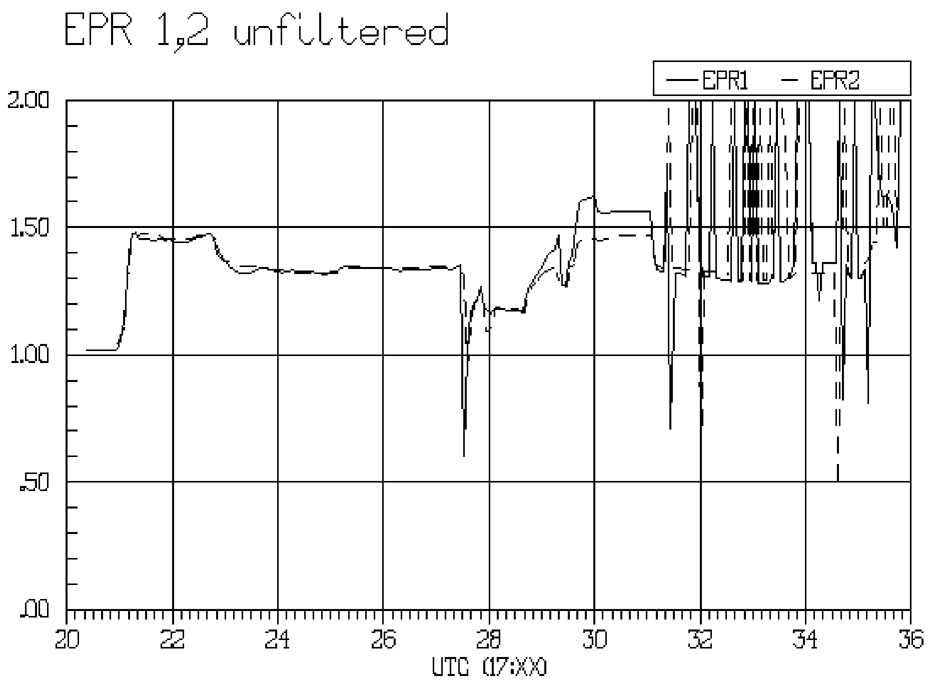


Fig. 2 Filtered EPR data from DFDR

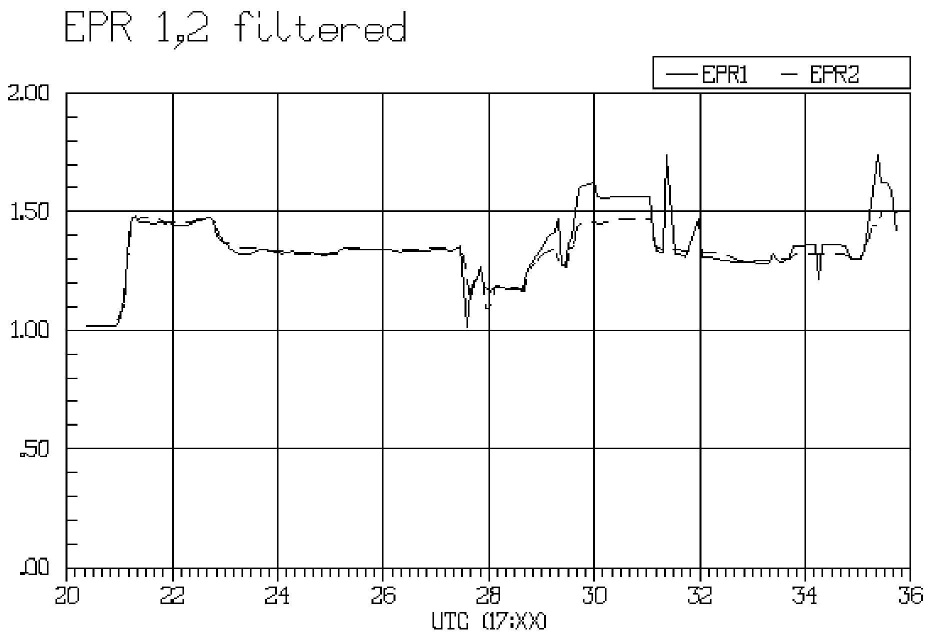

EPR 1,2 filtered
EPR1
EPR2
2.00
1.50
1.00
.50
.00
20
22
24
26
28
30
32
34
36
UTC (17:XX)

Fig. 3   Unfiltered rudder deflection data from DFDR

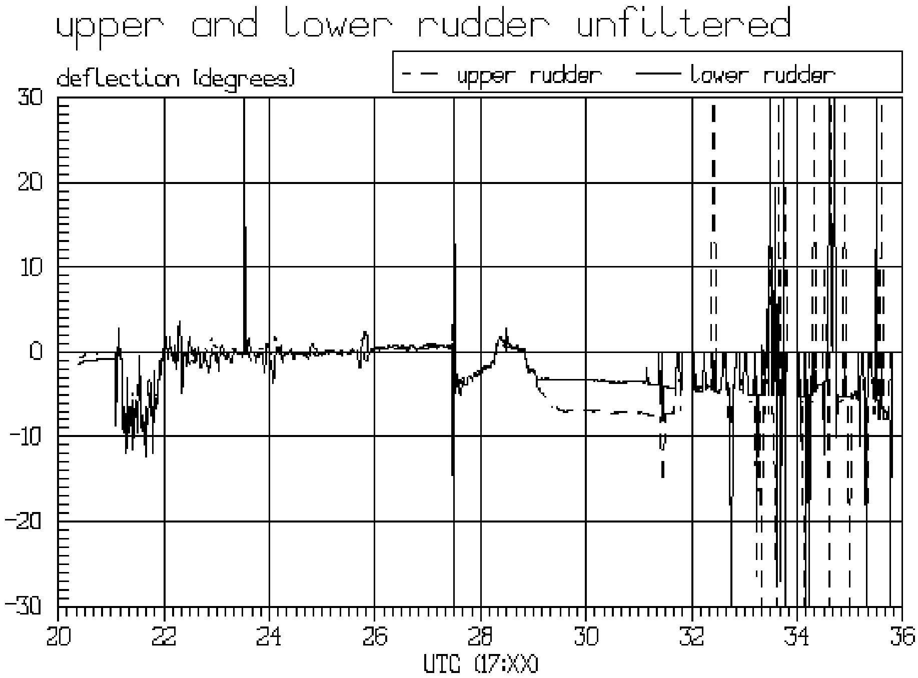
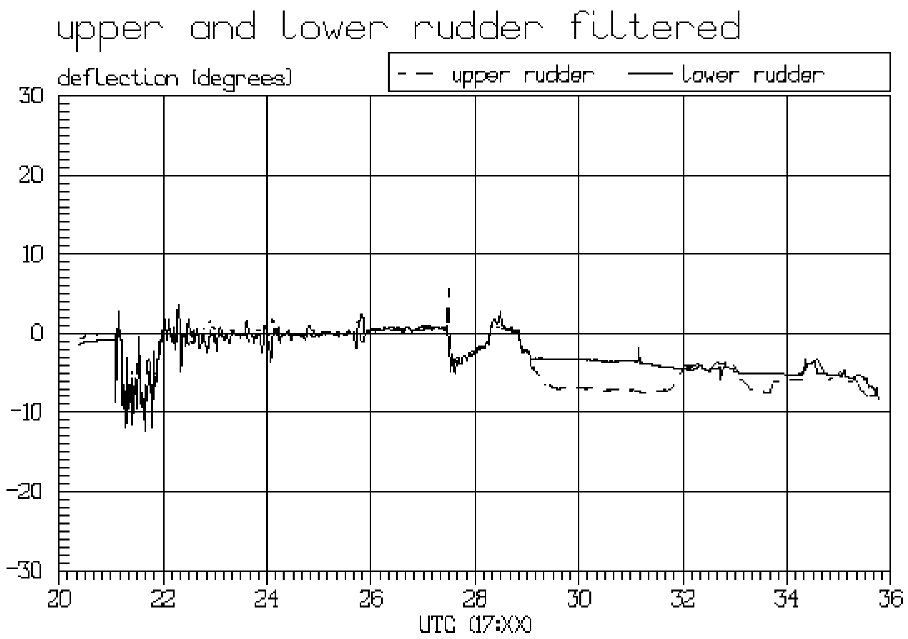


Fig. 4 Filtered rudder deflection data from DFDR



These figures clearly show the importance of this manual data reduction process in order to obtain understandable data. The importance of these data for the investigation will be discussed in a later chapter. As the data corruption was mainly caused by the fire damage to the DFDR tape and much time had to be spent on data reconstruction, one of the recommendations of the official aircraft accident report was:

Fire resistance of DFDR and CVR should be improved.

Other tools during the investigation were a training simulator of KLM Royal Dutch Airlines, the research flight simulator of the National Aerospace Laboratory NLR and one of the Boeing engineering simulators (M-cab).

Initially the investigation in the KLM simulator was used to verify the hypothesis, that leading edge flap asymmetry was a factor in the accident. No modifications were made to the aerodynamic programming of this simulator.
The NLR simulator group undertook further analysis in their research flight simulator with an aerodynamic model specially adapted to reflect some of the aerodynamic effects of the damage to the aircraft. Both simulations were restricted by the non availability of the correct engine model.
Also Boeing performed elaborate analysis and simulation in one of their engineering simulators including the proper engine simulation model and all the estimated aerodynamic effects caused by the damage to the aircraft. The final result after extensive work showed a very adequate representation of the data from the DFDR. Both RLD pilots from the investigation team were given the opportunity to fly this simulation. This proved to be instrumental in understanding the course of events.
Another important analysis tool was a so called energy analysis also being of major importance for the final understanding of the course of events. The composition of the RLD investigation team was also a factor of importance. Apart from the (at the time) RLD accident investigation experts the team comprised various

RLD specialists such as an engineering test pilot, stability and control and performance experts, engine, DFDR, ATC specialists and an operational expert, who also was an experienced Boeing 747 captain. Important outside help, support and knowledge was provided by El Al, Boeing and Pratt and Whitney experts, who performed an active role during the whole investigation. Special mention deserves a senior NTSB investigator who was of great assistance in the drafting of the initial report.

4. Damage to the aircraft

A brief summary is given of the damage to the aircraft. For more details the reader is referred to the official aircraft accident report.

Due to the separation of both engines and pylons on the right wing corresponding systems were lost. Therefore hydraulic systems 3 and 4 were inoperative. This in turn resulted in a significant reduction of the availability of the hydraulically driven primary and secondary flight controls.
Outboard trailing edge flaps have primary hydraulic control by system no 4, so hydraulic control of this system was lost. Inboard trailing edge flaps are driven by hydraulic system no 1 and therefore remained available. The trailing edge flap system also has alternate electrical control.
Roll control is by spoilers and in- and outboard ailerons. 66% of the spoilers were lost. All ailerons are driven by double actuators powered by two separate hydraulic systems. For all ailerons one hydraulic source remained available. However, the outboard ailerons are intended for low-speed flight only and are consequently locked out or deactivated, when the outboard trailing edge flaps are retracted.
The rudder control system consists of a lower and an upper rudder, both parts are powered by actuators with dual hydraulic supply. After engine separation one hydraulic source for each rudder part remained available. The rudder system also has a so-called rudder ratio changer. This device modifies the gearing between the rudder pedals and the rudder in such a fashion that with increasing airspeed at a given rudder pedal input the rudder deflection is reduced.
The elevator and stabilizer systems are not further discussed as it was determined that their functioning was not a factor in the accident.
The reduction of dual to single hydraulic source for the flight control actuators was analyzed and it was determined that in general adequate control power remained available.
The leading edge flaps have primary pneumatic control. Due to the engine separation the pneumatic manifold was open to atmospheric pressure. Also due to the interrelation of leading edge flap control and trailing edge flap position the leading edge flaps were most probably operated by alternate electrical means.

The fire warning system is a conventional dual loop system optimized to avoid false fire warnings. The standard conventional cockpit fire warning indications will only be triggered, if both loops sense a fire or a fault signal, provided both loops are selected. The switching logic is given in the following table:

Loop A sense	Loop B sense	Indication
fire	fire	fire
fire	fault	fire
fire	none	fault
fault	fault	fire
fault	none	fault

Fig. 5 Fire warning indication logic

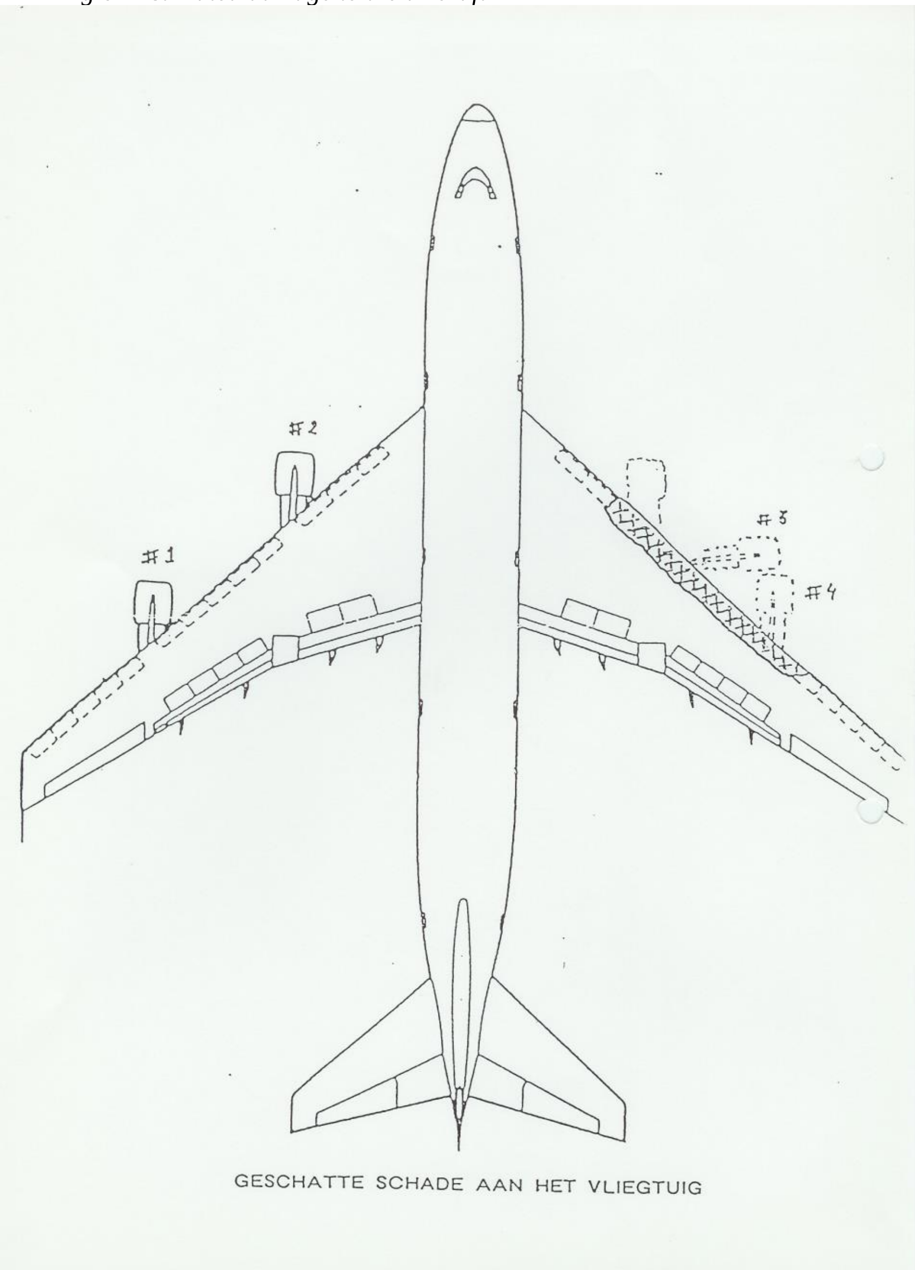
Due to the engine and pylon separation most probably there was a short circuit in both sensing loops, which causes a fire warning. The crew did report a fire warning on engine no 3.

As the fire warning may have influenced the decision making process of the crew that led to an early return to Schiphol, the official aircraft accident report contained the following recommendation:

Review design philosophy of fire warning systems, to preclude false warnings upon engine separation

The estimated damage to the wing based on wreckage information is given in the following figure.

Fig 6   Estimated damage to the aircraft

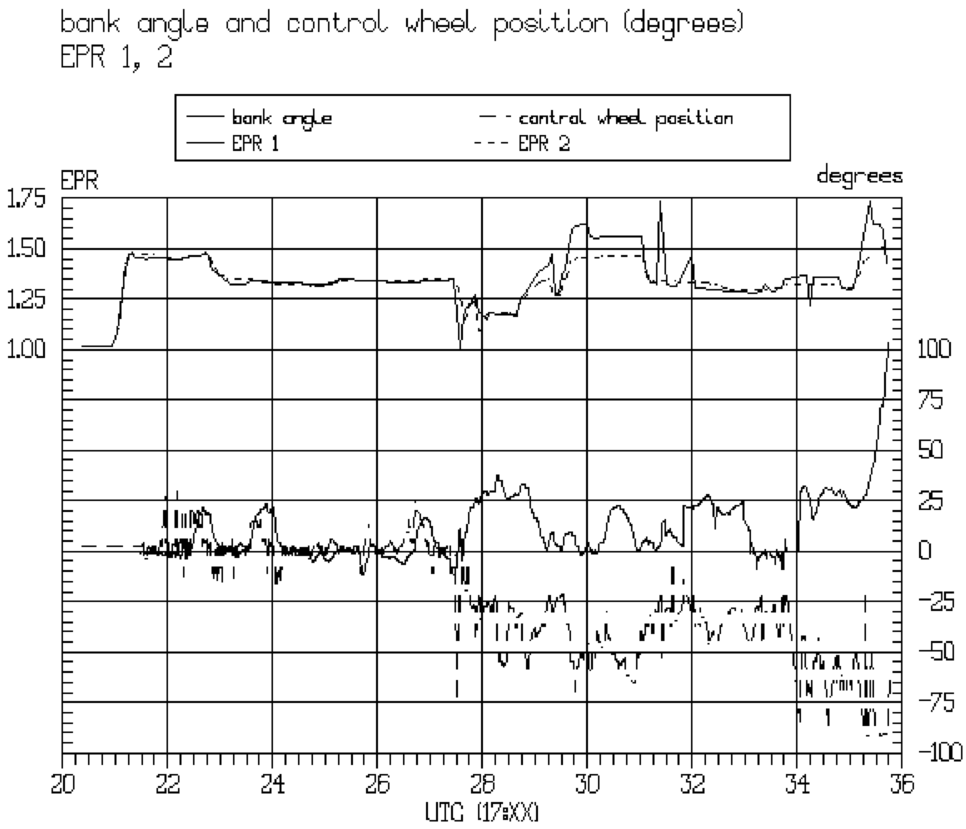


Some months after the El Al accident on another Boeing 747 freighter aircraft an engine/pylon separation (no 2) occurred. The aircraft was able to return to Anchorage with considerable control difficulties. The NTSB report of this accident contains some pictures, that give an indication of the extensive damage to the wing leading edge structure due to this engine separation. The aerodynamic, performance and stability and control effects of the wing damage will be further discussed in a later chapter of this paper.

5. Aircraft condition directly after engine separation

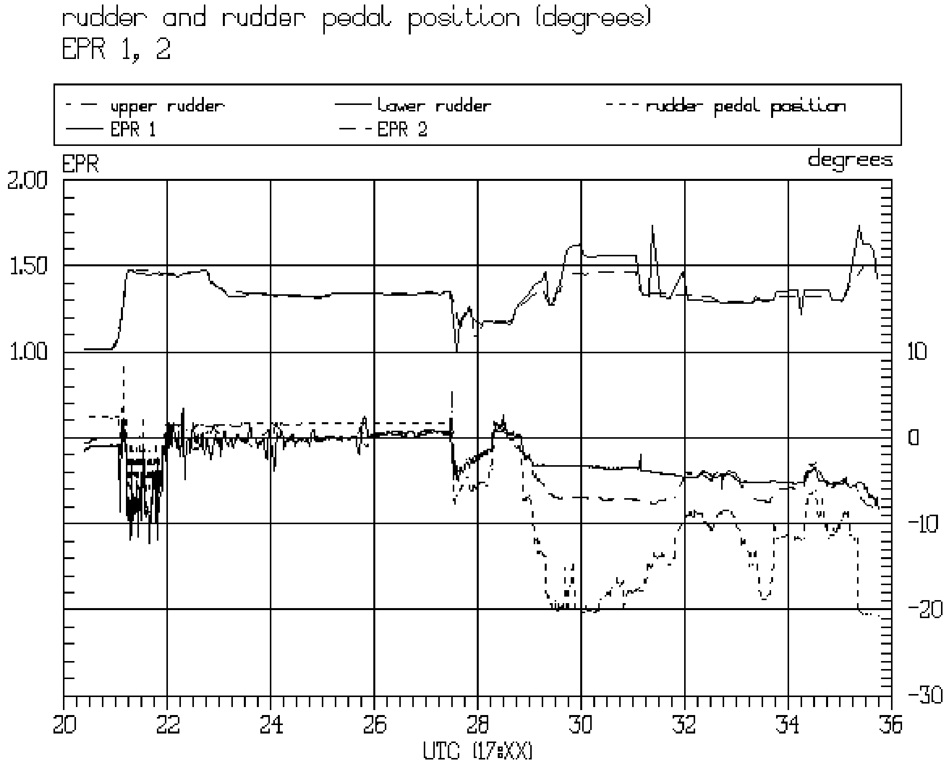
From the DFDR the following situation emerged directly after engine separation. At a speed of 270 kts and Go-around thrust the aircraft appeared to be marginally controllable. The position of the flight controls (60 % left wing down aileron wheel deflection and full rudder pedal position) was rather unusual. Standard Boeing flight techniques in engine inoperative flight are rudder pedal application until the aileron wheel is neutral with Maximum Continuous Thrust (MCT). Even with Go-around thrust such a large aileron wheel deflection would be unusual. The data from the DFDR are given in the following two figures.

Fig. 7   Bank angle, aileron wheel position and EPR



bank angle and control wheel position (degrees)
EPR 1, 2
bank angle
control wheel position
EPR 1
EPR 2
EPR
degrees
1.75
1.50
1.25
1.00
100
75
50
25
0
-25
-50
-75
-100
20
22
24
26
28
30
32
34
36
UTC (17:XX)

Fig. 8 Rudder deflection, rudder pedal position and EPR



Another unusual aspect was, that the V_{MCAn-2} (minimum control speed in the air with two engines on one side inoperative) for this aircraft is in the order of 150 kts. At the much higher speeds, that were flown varying between 280 and 260 kts, the flight crew experienced considerable control difficulties, suggesting a much higher V_{MC}. This is contrary to the intuitive general assumption, that aircraft control capability improves with speed.

Apart from the unusual flight control positions, there was a fire warning on engine no 3 as reported by the crew and a fire warning on engine no 4 may have been possible as well. This however could not be determined from available data. There must have been numerous other abnormal indications in the cockpit due to the loss of two hydraulic systems, two electrical generators and damage to various other systems. Although this could not be determined with any certainty, the investigation team assumed, that the crew was not aware of the separation of both engines.

6. Choice of landing runway

From available data it could be determined, that the crew very quickly decided to return to Schiphol after engine separation. The choice of landing runway was initially very surprising, because the crew opted to land on runway 27, where the existing wind had a north easterly direction with 21 knots (040/21). This means a tailwind component of 13 kts and a crosswind component of 16 kts (from the unfavourable side, taking into account the effect of the double engine failure.)

There are a number of reasons why the crew may have taken this decision. It should be realised, that this is based on what the investigation team considers to be the best estimate of what the crew may have thought and considered. As the CVR was never found, there is only very limited evidence of what transpired in the cockpit.

- The crew may have thought, that one or two engines were on fire, and that they were unable to extinguish those fires. This is supported by the fact, that the Boeing recommended speed for an unextinguishable engine fire was flown.
- The weight of the aircraft at the time of engine separation was above the weight at which a Boeing 747 can maintain level flight with two engines inoperative. For the particular aircraft this weight was 320 metric tons in an undamaged configuration. This number was ready knowledge for El Al pilots, as indeed for most pilots. This also explains the decision to start dumping immediately, which was noted by many witnesses and could be verified by photographs.
- During the public hearing by the Netherlands Aviation Safety Board El Al offered the hypothesis, that the crew may have thought, that the effects of the engine separation, that must have been quite noticeable in the cockpit, were caused by a missile attack.
- The control situation after engine separation was quite unusual as explained above.
- The crew was familiar with Schiphol Airport, therefore probably knew runway 27 was the longest runway and may even have seen the runway from the position, where the engines separated.

Considering all these points, the decision to choose runway 27 for landing is understandable.

7. Aerodynamic considerations

7.1. General

The analysis of the aerodynamic effects, that contributed to the final loss of control, was very complex for a number of reasons:

- The combination of stability and control effects on one hand and the performance effects on the other hand caused by the unique damage to the aircraft.
- The interaction between thrust, speed, roll and directional control and side slip effects in combination with flight with asymmetric thrust. Note: on many aircraft there is an appreciable adverse effect of decreasing bank angle on minimum control speed. Originally this was thought to be a factor, but this turned out to be untrue.
- The difficulty of obtaining trustworthy analytical data on the performance effects caused by the damage.

7.2. Floating right outboard aileron

From the DFDR it was observed, that after engine separation the right outboard aileron gradually moved to a 6 degrees trailing edge up position. As explained earlier the outboard ailerons are locked out, when the outboard trailing edge flaps are in the UP position. In this case the aileron is kept in position by trapped hydraulic fluid. Probably due to the loss of hydraulic system 3 and 4, which drive this outboard aileron, the hydraulic locking function was partially lost and the aileron started moving slowly due to the aerodynamic hinge moments caused by airloads, probably also influenced by the increasing angle of attack. This in turn caused a roll moment right wing down.

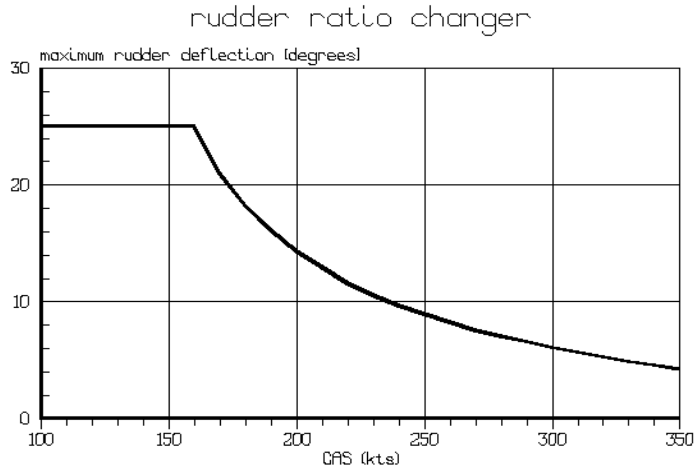
Therefore the official aircraft accident report gives the following recommendation:

> *Review flight control design to ensure that flight control surfaces do not contribute adversely to airplane control in case of loss of power to a control surface*

7.3. Rudder ratio changer

As explained earlier the rudder ratio changer modifies the gearing between rudder pedals and rudder surface. This also means, that the maximum rudder deflection is reduced with increasing airspeed. This is illustrated in the following figure, where an inverse quadratic relationship can be seen between airspeed and rudder deflection at full rudder pedal input.

Fig 9 Rudder deflection as a function of airspeed

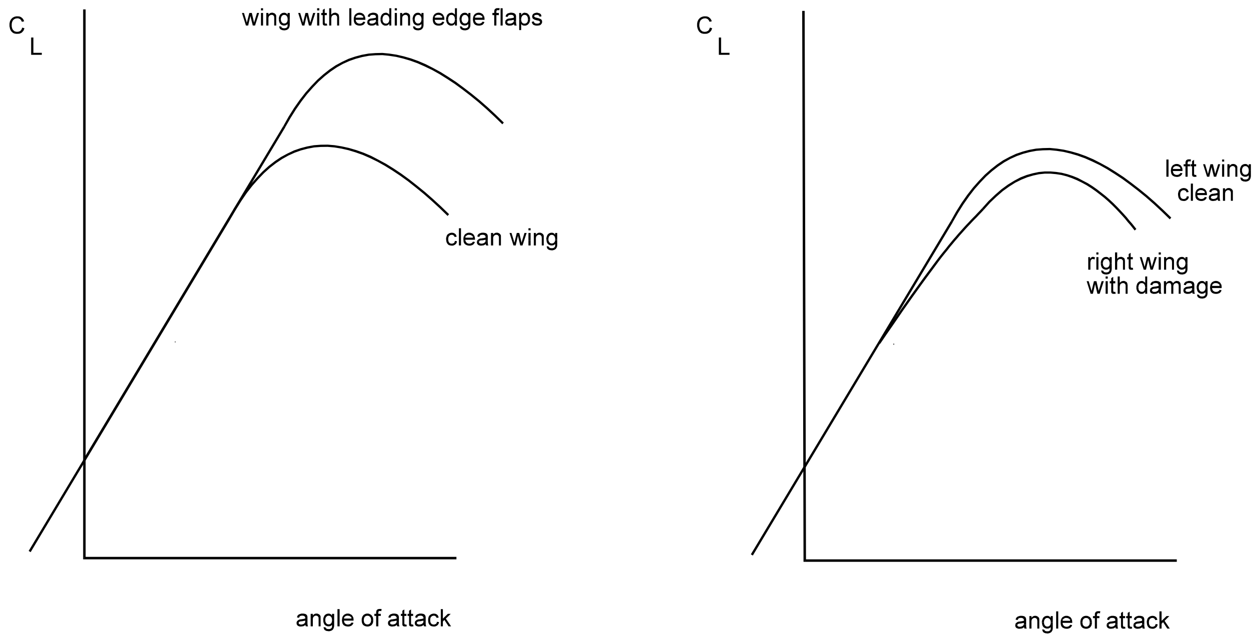


This gearing is chosen to protect the vertical fin against excessive airloads due to full rudder pedal input at high speed. This keeps the maximum side load on the tail constant as airspeed increases. It will not be surprising that there is an inverse quadratic relationship between speed and rudder deflection.
Another effect of relevance and well known to pilots flying Boeing aircraft is that, with constant thrust and varying airspeed at a fixed rudder pedal position, the aileron wheel position will be constant as well during engine-out flight. This is very convenient for the pilot performing an engine-out initial climb-out and acceleration after take-off. It also means that the lateral control margins remain constant with speed, which is in contrast to the intuitive assumption, that controllability margins will increase with increasing airspeed. The above can be verified by analysing the lateral-directional equations of motion. The analysis is outside the scope of this paper.

7.4. Angle of attack effects

The extensive damage to the leading edge of the right wing caused a significant asymmetric roll effect. Initially it was thought, that the final roll to the right was caused by the well known effects of leading edge flap asymmetry. This was checked in a simulator, but the effects of a total leading edge flap asymmetry would have caused a much more abrupt rolling moment, than was observed on the DFDR. Also it is well known from simple aerodynamic theory, that this rolling moment will suddenly occur, when a certain angle of attack is exceeded. This effect is illustrated in the following figure, where on the left side the classical lift curve is shown for a wing with leading edge flaps extended and retracted (clean wing). On the right side the estimated effect of the wing damage due to engine/pylon separation is shown:

Fig 10   Lift curve for various wing configurations



The right figure shows, that with increasing angle of attack there is a gradual degradation in lift on the damaged wing as compared to the clean wing. This results in a rolling moment in the direction of the damaged wing, that gradually increases as the angle of attack increases or if the speed decreases. In addition if a turn in the direction of the damaged wing is initiated at constant airspeed, the rolling moment will further increase due to the increase in load factor and corresponding increase in angle of attack. This hypothesis could be verified from DFDR data.
It should also be noted, that the loss of the engine pylons has an significant effect on the lift of that wing.

7.5. Thrust application

Just before the final loss of control a significant thrust input was made with a delayed rudder application. When applying asymmetric thrust without corresponding rudder input the aircraft will yaw in the direction of the "dead" engine, side slip will build up, which causes a rolling moment in the direction of the "dead" engine.
The thrust application and delayed rudder application can be seen in Fig 8.

7.6. Energy analysis

As explained above initial analysis was hampered by lack of a suitable aerodynamic model representing the performance effects of the damage to the aircraft. As it is very complex and time consuming and requires very special expertise and data to make such an aerodynamic model, the decision was made to employ energy analysis to integrate the data from the DFDR.
The main advantage of this technique is that no a priori aerodynamic model or drag polar is required and data from the DFDR can be used. Another advantage is that the effects of speed, height and vertical speed, that were very variable, can be integrated. Basically the total energy of the aircraft is calculated as the sum of potential and kinetic energy.
A limitation of this analysis technique is that conclusions are only valid for the conditions analyzed (e.g. thrust and load factor). Therefore careful correlation with these data is necessary. The conclusions from this analysis will be discussed in the next chapter.

8. Synthesis of the final loss of control

This chapter summarizes all the aerodynamic effects discussed so far. A positive effect is left wing down, a negative effect is right wing down. The synthesis is split in a control and a performance section.

8.1. Aircraft control

8.1.1. Roll control

The only positive effect of the separation of the two engines on the right side was the loss of weight causing a roll moment to the left.

All other effects were negative.
As explained previously the floating right outboard aileron caused a right wing down roll moment. The increasing roll moment due the different lift curves for both wings is explained above as well. The same applies for the roll moment due to thrust increase on engines 1 and 2 with delayed rudder application.

The combination of adverse rolling moments could finally not be coped with as the roll control was degraded as well. The outboard ailerons were not available due to flap lockout discussed previously. It is not unreasonable to assume that the effectiveness of the right inboard aileron was reduced since it was located behind that part of the wing, that was damaged by the separated engine and pylon no 3. Due to the loss of two hydraulic systems a significant part of the roll spoilers was also not available.

8.1.2. Degradation of directional control

From the DFDR it can be observed, that about 2 minutes after engine separation the lower rudder is restricted in its maximum deflection although not quite at a constant angle. Despite intensive efforts by the investigation team and Boeing it was not possible to find an acceptable explanation. However it most certainly contributed to the degradation of directional control. This unexplainable rudder split can be seen in Fig. 4 and 8.
Other adverse directional effects were caused by the loss of thrust on engines 3 and 4 (obviously) and the EPR (thrust) split on engines 1 and 2.
Furthermore the extra drag of the damaged right wing would have caused an increase in the adverse yawing moment.

8.2. Performance aspects

The position of the leading edge flaps during the last part of the flight is uncertain. From the wreckage it could be determined, that the leading edge flaps were in a partly extended position. However, since just before the final loss of control the captain commanded to raise all the flaps, as heard on the ATC tape, it may be possible that the leading edge flaps were initially extended and retracted later. Theoretically various other possibilities exist. DFDR data were not conclusive as to the actual position. If the leading edge flaps were extended, they would have increased the drag, and therefore degraded the performance capability of the aircraft, that was already significantly degraded due to the damaged wing and the loss of thrust on engines 3 and 4.

8.3. Results of energy analysis

From the energy analysis the following conclusions were drawn related to the performance capability of the damaged aircraft:

- There was marginal level flight capability at a speed of 270 kts and Go Around thrust.
- There was no level flight capability at a speed of 270 kts and MCT thrust.
- Below a speed of 260 kts the performance of the aircraft progressively deteriorated.

The final application of Go Around Thrust was probably a response of the crew to the progressively deteriorating performance condition of the aircraft resulting in an increasing vertical speed close to the ground. The position of the leading edge flaps may have contributed to this.

In conclusion the last part of the probable cause in the official aircraft accident report is quoted verbatim:

> *After engine separation this subsequently left the flight crew with very limited control of the airplane. Because of the marginal controllability a safe landing became highly improbable, if not virtually impossible.*

9. The dilemma

One of the important lessons, that can be relearned from this investigation is the dilemma between controllability and performance.
If an extreme situation develops e.g. approaching the ground rapidly it is understandable, that a pilot will use all the thrust, that is available to stop the sink rate. However when controllability limits are exceeded, this will result in an immediate loss of control, whereas limiting the thrust increase to the extent, that the aircraft will remain controllable, may in certain circumstances offer additional options, although not necessarily avoiding a crash. The official aircraft accident report gives the following recommendation on the subject:

Evaluate and where necessary improve the training and knowledge of flight crews concerning factors affecting aircraft control when flying in asymmetrical conditions such as with one or more engines inoperative including:

- *use of thrust in order to maintain controllability*
- *advantages and disadvantages of direction of turn*
- *limitation of bank*

10. Direction of turn in case of engine failure

In general during flight with asymmetric power, when a turn is made into the direction of the "dead" engine, it is easier to manoeuvre, but there is less controllability margin, when additional thrust is applied. For the turn direction away from the dead engine the opposite is true. This applies to all aircraft.
In the particular case of El Al flight 1862 there was an additional effect due to the difference in lift curves for both wings. The rolling moment would be increasing in a right wing down direction when making a right turn due to the increase in angle of attack. This had the effect of steepening the turn. When left turns were made, this rolling moment would have created a tendency to roll out of the turn.

Many pilots know the old rule: *"always turn away from the dead engine ".* This rule of thumb dates back from the times of propeller/piston powered aircraft. Obviously the effect of propeller slipstream on roll moment with asymmetric power is the background.
Modem aircraft in general have more than adequate control margins to manoeuvre in either direction of turn also with asymmetric thrust. Because it is impossible to foresee what the situation in actual operation might be, it should always be left to the pilot which direction of turn is most appropriate. A hard rule always to turn in a certain direction with engine failure is therefore not appropriate.

At present on most aircraft the bank angle will be limited to 15 degrees at slow speeds (typically V_2) during one engine inoperative flight. This is to limit stall speed increase with bank angle.
In addition it is good operating policy to limit bank angle to 15 degrees also, when controllability is in doubt. If there is any control problem related to angle of attack, the effects of this problem will be minimized when bank angles and load factors are kept small.

11. External inspection

The official aircraft accident report contains the following recommendation:

Investigate the advantages of installation cameras for external inspection of the airplane from the flightdeck.

The background for this recommendation is, that it is assumed, that the crew of El Al 1862 never was aware that two engines were physically separated from the aircraft. The geometry of the Boeing 747 is such that from the cockpit the outboard engines can just be seen, provided a lot of effort in bending over is made to do so. Therefore external cameras seem an attractive solution.
However, it is noted that careful study is required to ensure applicability under all conditions, including night and flight in clouds. Moreover the addition of displays in the cockpit raises questions about the integration of the newly available information in existing procedures. The Human Factors aspects need careful evaluation.

A number of experiments with external cameras are ongoing at British Airways in collaboration with the UK CAA and El Al. Also Fokker Elmo is working on these systems.

Presented to the Netherlands Association of Aeronautical Engineers (NVvL) on January 26, 1995