Using Physical Evidence from More Complex Mid-air Collisions

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The views expressed in this paper are those of the authors and not necessarily the views of the NTSB.

Introduction

Mid-air collision investigations are one of the most interesting investigations faced by the professional air safety investigator. While increasing technology has reduced the number of mid-air collisions, they continue to happen and present the investigator with some unique challenges. This paper is a review of the principles used in the investigation of basic mid-air collisions and how those same principles can be applied to even more complex investigations. The basic principles of a mid-air collision investigation have been examined in several sources but the discussion here will be limited to the ICAO "Manual of Aircraft Accident Investigation" (1) and the simplified approach to using the ICAO procedures previously outlined in the ISASI Forum by one of the authors titled "Using Physical Evidence From a Mid-Air Collision". (2)

The investigator may be able to use flight recorder information, radar data and even witness statements to assist in the investigation. However, these sources of information may not be available on all accidents and in some cases are not as accurate as the physical evidence. The physical evidence left from a mid-air collision can tell you precisely the relative headings of the two aircraft involved at the time of the collision. Combined with other data like radar, you will end up with a more complete picture of the collision sequence. Of course there will also be situations where the physical evidence is the only data available. In that case, the analysis of the scratch marks will be the only basis for determining the collision angle.

A review of the ICAO Manual approach to using physical evidence

The techniques developed in this paper and the previous paper on the subject by one of the authors varies somewhat from Appendix 11 of the Fourth Edition of the ICAO "Manual of Aircraft Accident Investigation". The ICAO manual, for example, refers to 19 "Rules of Thumb" that provide guidance for analyzing scratch marks. While these "Rules of Thumb" are valuable, this paper uses a simpler approach to the analysis of scratch marks that is easier for the investigator to remember and use while at an accident scene. By adding the concept of convergence angles onto the ICAO approach, the investigator is able to more quickly determine what the visibility was from each cockpit. (See Attachment A) If we have a scratch mark on an aircraft that is going from the leading edge to the trailing edge of the wing forming a 20-degree angle with the longitudinal axis we know that the convergence angle of the second aircraft was also 20 degrees from the 12 o'clock position at the moment of impact.

Convergence angles have to be based on heading rather than track in order to establish a valid visual perspective for each pilot. Once these angles are established, you can replicate the visibility from a cockpit with fairly good accuracy. A visibility study can be done with a computer to provide a graphical plot of what the pilot(s) could have seen from the cockpit. The pilot's visibility can also be assessed manually by reconstructing the pilot's seated height and seat location in a similar aircraft and then determining what is at the convergence angle.

Using scratch marks to determine the collision angle always gives a relative angle between the two aircraft headings rather than the actual compass headings of the aircraft.   This is actually a very helpful result in that we need the relative headings of the two aircraft to determine each crew's visibility of the other aircraft. However, while the scratch marks can tell you the relative attitude of one aircraft compared to the other, they will not give you the absolute heading of either aircraft. Likewise, the scratch marks may tell you the relative attitudes of the aircraft to each other, you will not know what the attitude of either aircraft is in reference to the horizon.

The techniques discussed in this paper have been limited to determining horizontal angles of convergence and collision. However, the same techniques will work to establish the vertical angles of convergence by using scratch marks from vertical surfaces rather than the horizontal surfaces. The ICAO Manual uses 8 pages to explain how to calculate the collision angle when there is both horizontal and vertical motion involved. While this material is excellent, there is an alternative approach which is less time consuming. Simply solving for the horizontal angle and the vertical angle separately and then combining the results at the end will give the same result as the ICAO approach.

Basic ways to calculate a collision angle using scratch marks

It is important to note at this point that a common mistake made in evaluating a mid air collision is for the new investigator to assume that the scratch mark (or structure deformation) is synonymous with the track of the other aircraft. Investigators will sometimes find themselves sighting down the scratch mark as though that represents the flight path of the other aircraft. Occasionally, even experienced investigators can be seen placing a part of an aircraft wreckage into a matching damage on the second aircraft as though that was the way the two aircraft collided. In reality, a scratch mark is a combination of the movement of two different bodies in motion. (See Attachment B) Only when one of the aircraft is not moving or the second aircraft is approaching from the 12 o'clock or 6 o'clock positions, will the scratch marks show the direction of travel for that aircraft.

When both aircraft have good scratch marks

When both aircraft have reliable scratch marks, solving for the collision angle is a fairly simple process. Since the scratch marks are the same as the respective convergence angles, it is simply a matter of subtracting the two scratch mark angles from 180^0 to get the collision angle.

When only one aircraft has a good scratch mark but the speeds of the two aircraft can be determined or estimated

When only one aircraft has a reliable scratch mark, it is necessary to have the speeds of the two aircraft in order to solve for the collision angle. While any estimate introduces some error into the final results, a range of probable speeds can be used and the resulting range of probable collision angles will provide useful information to the investigation. The variation in one general aviation accident was only about four degrees. While it's desirable to have more precise calculations, this range can still be very useful for a visibility study.

Extending the techniques to more complex accidents

Using propeller slashes to calculate a collision angle

Using the exact same physics as in the basic approach we can extend the techniques to more complex accidents. For example, when there are propeller slashes left on an aircraft, we can calculate the “collision angle” between the propeller blade and the aircraft with the slash marks. Working backwards, we can then calculate the collision angle between the two aircraft.

A propeller tip moving through space is the combination of the propeller blade motion and the aircraft motion. Since propeller blades are a fixed dimension and rotate within certain expected RPM ranges, we can calculate the speed of a prop tip for any given RPM. Obviously, constant speed propellers and aircraft with known power settings will give more accurate results, but a range can be used to calculate a collision angle range much like we do when only the speed of one aircraft is known.

By using the diameter of the propeller, direction of rotation for the propeller and the RPM of the propeller, a calculation for the prop tip speed can be established using standard trigonometric functions. (Attachment C) Since the prop is always providing thrust at a 90^0 angle with the longitudinal axis of the aircraft, we can use the square of the prop vector and the square of the aircraft vector to get the square of the combined vector, which represents the prop tip moving through space. Combining this prop tip moving through space with the movement of the second aircraft allows us to solve for the collision angle between the prop tip and the second aircraft. Then, using basic geometry, we can determine the collision angle between the two aircraft.

Case Study #1 Beech King Air/Piper Navajo collision with only one prop slash

A Beech King Air collided with a Piper Navajo near a VOR while both airplanes were in cruise flight in VFR conditions. Both aircraft were substantially damaged but landed safely. Interviews with the crews revealed that they were not aware of the other aircraft until just before the collision. The only reliable scratch mark was a prop slash on the underside of the right wing of the King Air. The angle between the prop slash and the longitudinal axis of the Beech was 102 degrees.

The Piper prop tip speed was calculated at 456 knots using the diameter of the propeller and the RPM of the propeller. This was then combined with the 244 knot speed of the Piper aircraft to produce a resultant 517 knot vector. Since this is the vector that actually produced the slash on the Beech, we can combine the prop tip vector with the Beech vector to calculate a collision angle of 54 degrees between the Piper prop tip and the Beech. (Angle C in Attachment C) While interesting, this number in itself is only part of the collision angle between the two aircraft and useless to the investigator by itself since we really aren’t interested in the collision angle between the prop tip and the aircraft. What we need to ultimately determine is the collision angle between the two aircraft themselves.

To determine the second part of the collision angle we first need to use basic trig functions to calculate the angle between the final prop tip vector and Piper aircraft vector. While this number once again isn’t a particularly useful number, it does allow us to then calculate the remaining angle in our drawing (Angle D in Attachment C) to find the collision angle between the two aircraft. From basic geometry we know that when a straight line intersects two parallel lines, the opposite interior angles are equal. This allows us to substitute the angle between the resultant prop tip vector and the Piper (Angle A in attachment C) for the remaining part of our collision angle (Angle D in attachment C) with a resulting collision angle of 116 degrees.

For many of the calculations in the mid-air collision diagram, the Law of Sines is the best equation to use. However there is one significant exception when it comes to solving for the closure speed when using only a single prop slash. In this case it is necessary to use the Law of Cosines.

Case Study #2 Midair collision between two Beech Bonanzas

In the afternoon of June 8, 2000 an accident with a Beech Bonanza of the KLM flight academy (KFA) was reported. The aircraft (registered PH-BWC, aircraft number 1) had crashed in a field. The instructor and two students who were on board were fatally injured.

On my way to the accident site I was informed that another aircraft was involved. It was from the same school and also a Beech Bonanza. (PH-BWD, aircraft number 2) The instructor had made a successful emergency landing and was uninjured. The two students that were on board this aircraft suffered back injuries.

The accident happened during a sunny day in uncontrolled airspace south of Groningen Airport Eelde CTR, the home base of the KLM flight academy. The KFA uses this area frequently for training flights.

The wreckages of the two aircraft were found approximately 1.7 nautical miles from each other.

Aircraft 1 was found with the nose section (engine, propeller and nose gear) separated from the aircraft. The distance between the main wreckage and the nose section was approximately 50 meters. The main wreckage (wing leading edge) showed traces of an almost vertical impact. The tail section was undamaged.

Aircraft 2 was found in a meadow. From the track in the meadow it could be determined that a rather smooth gear up landing was executed. The cockpit roof was heavily damaged and scratched.

A closer look into the damage of aircraft 2 revealed the following:

- Tail section undamaged
- Right upper wing undamaged
- Left upper wing: dented and partly covered with a black greasy substance (show picture)
- Left aileron: Heavily damaged, partly disappeared and pushed in neutral position to the outer side of the wing. (show picture)
- Left lower wing: (show picture)
    1. Slash marks in wing and aileron corresponding with a propeller that turns to the right and passes underneath the wing (roughly speaking) from front to rear.
    2. A hole, just outside the wheel doors, that appears to have been made by a soft body. Inside there are traces of a black material, probably rubber.

Analyses

The heavily damaged and scratched roof of aircraft 2 showed clearly that there was a collision with something above the aircraft. The propeller slashes in the left lower wing pointed to a collision with an aircraft from below.

How was it possible that aircraft 2 was heavily damaged both at the top and at the bottom?

Was a third aircraft involved?

Where did the big hole in the left lower wing come from?

We think the sequence of events was as follows:

- Both aircraft were flying in the same direction.
- The bottom of aircraft 1 came in contact with the roof of aircraft 2, probably during a pull up of aircraft 2.
- Aircraft 1 “slid” to the left over aircraft 2.
- The left inner wing and leading edge “supported” aircraft 1 just behind the engine section.
- The engine and nose gear separated from aircraft 1 due to acceleration forces during the collision, leaving dents and oil on the left upper wing of aircraft 2.
- The nose section with the engine still running turned upside down and passed underneath the left wing of aircraft 2.
- The propeller, still turning clockwise made the prop slashes, damaged the left aileron and pushed it outwards.
- Because the clockwise turning propeller was cutting the wing, the engine itself tended to turn anti-clockwise (action = reaction)
- During this process the nose gear came out of the bay and was slammed against the bottom of the wing, causing the hole.

Later when the radar data and witness statements were available we found out the following:

- The two aircraft were flying in formation
- Both instructors had come up with the idea to use their instruction slots for a birthday greeting for another KFA instructor, who was the father of the instructor who survived the accident. Aircraft 1 crashed a few hundred meters from his home.
- The aircraft passed the house two times at low altitude (below 300 ft). During the second pass the collision occurred.
- During the second flyby there is no transponder signal from aircraft 1.

Beside the investigation into the direct cause of the accident the Dutch Transport Safety Board performed an investigation into the safety culture of the academy, which was state owned until 1990. Also the role of KLM as owner of the flying school and the CAA-NL as former “owner” and as organization responsible for the oversight was investigated.

Outline of the findings and causal factors related to the root causes of the accident:

Findings

- Neither one of the instructors was trained in formation flying.
- The formation flight was not authorized and not reported to operations or ATC.
- Because of their position the two instructors should have set the example should not even have considered this flight, especially not with students on board.
- At the time of the accident the KFA did not have a head of training nor a flight safety officer.
- The KFA board did not take “adequate measures” to keep the quality of the group of instructors on the recommended level.
- The KFA board did not implement and maintain a good working safety management system and did not create the conditions for the proper safety culture. This was one of the reasons that important positions were vacant.
- The KLM, as the owner of the academy, developed less activities to enhance safety, the safety management system and the safety culture than can be expected from an owner of a flying school (Specially when the owner is an airline and has the necessary knowledge to enhance a safe operation)
- The oversight of CAA-NL was insufficient.

Causal factors

- Absence of a just safety culture as a result of a lack of adequate measures by the KFA management.
- The absence of adequate activities of the owner of the academy.
- The insufficient overview by CAA-NL

Recommendations

To the KLM flight academy:

- Develop an adequate safety management system and incorporate a non punitive safety reporting system with feedback to all participants and encourage instructors and students to report occurrences

To KLM

- As owner of the KFA set requirements in relation to the safety, the safety management system and the safety culture. Keep oversight by requiring reports and performing audits.

To CAA-NL

- As civil aviation inspectorate of the KFA set requirements in relation to the safety, the safety management system and the safety culture. Keep oversight over the implementation and execution by requiring reports and performing audits.
- Investigate the possibility of requiring limited registration of flight data for aircraft operated by approved flying schools, for example by flight data recording.

Remark: Shortly after the accident a number of safety actions were taken by the KLM flight academy.

Summary

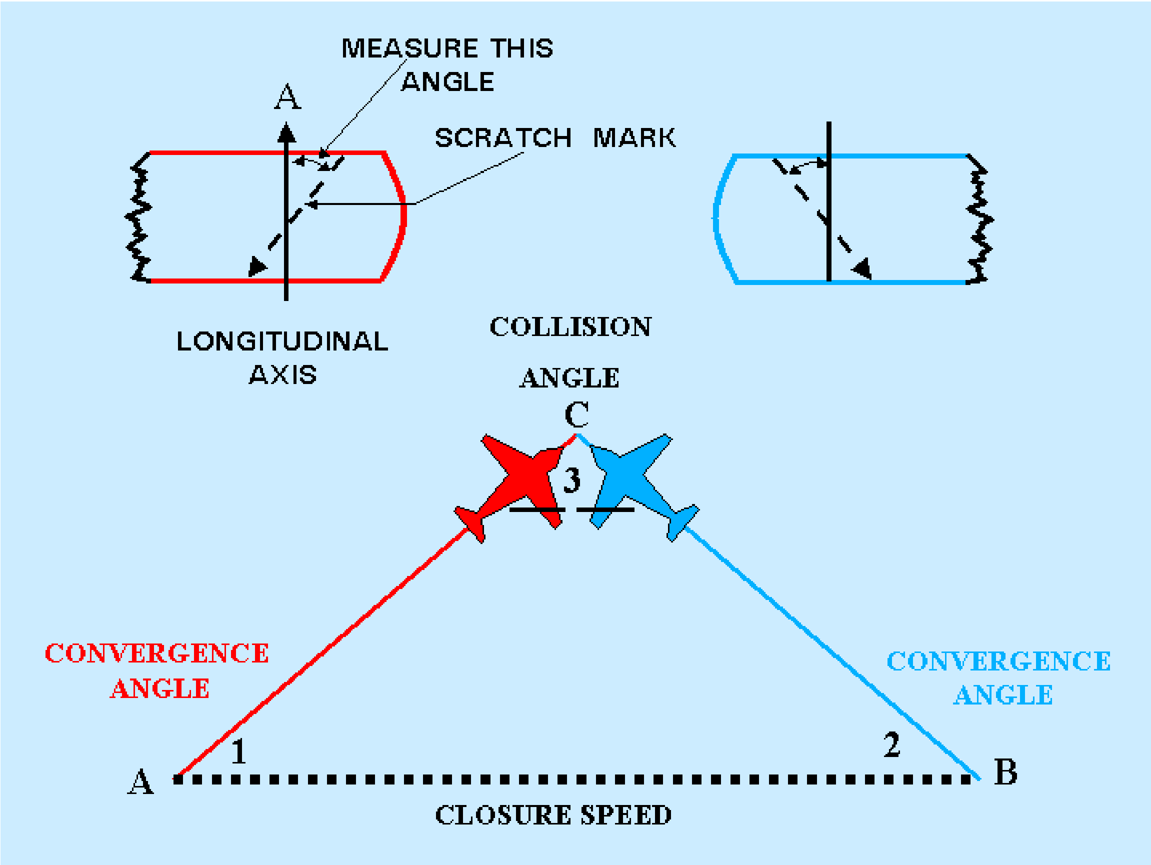
The aircraft wreckage from a mid-air collision can provide valuable information to the investigation process. The techniques in this paper provide a framework for expanding the basic mid-air collision investigation principles to more complex accidents. By properly documenting the scratch marks created from a mid-air collision the collision and convergence angles can be mathematically derived even in some of the more complex cases.

Notes

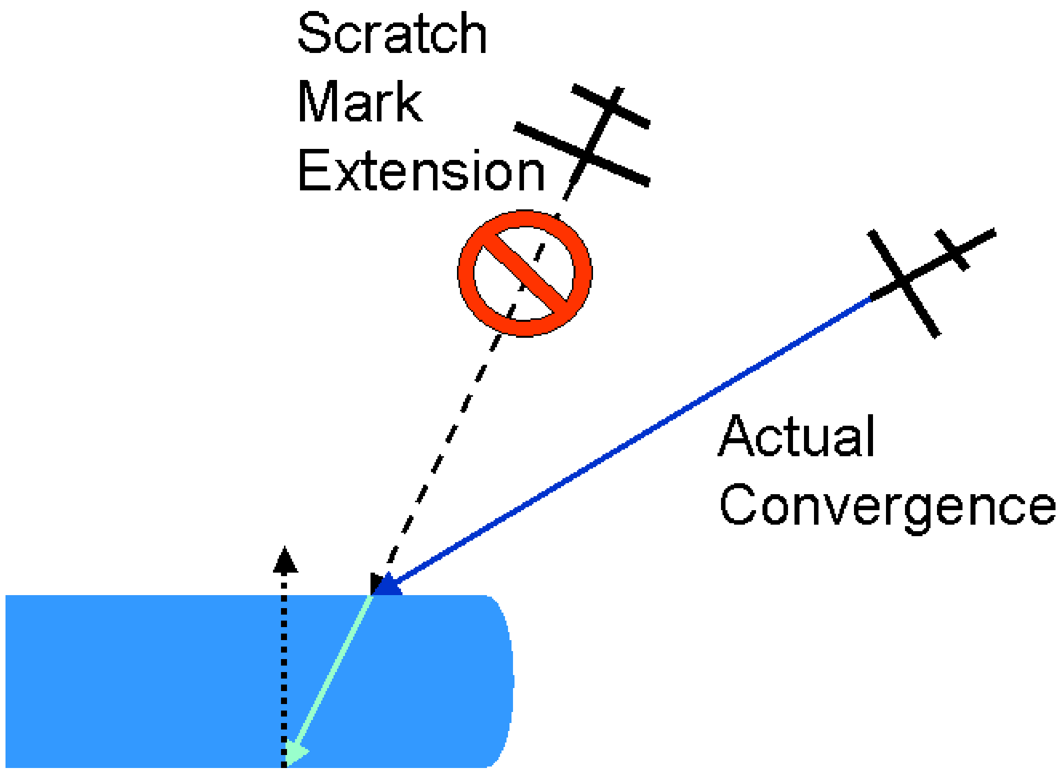
(1) Manual of Aircraft Accident Investigation, Fourth Edition, 1970 Doc 6920-AN/855/4

(2) Investigating Mid-Air Collision Accidents, Keith McGuire, ISASI Forum January-March 2002, Vol 35, Number 1

ATTACHMENT A



ATTACHMENT B



ATTACHMENT C