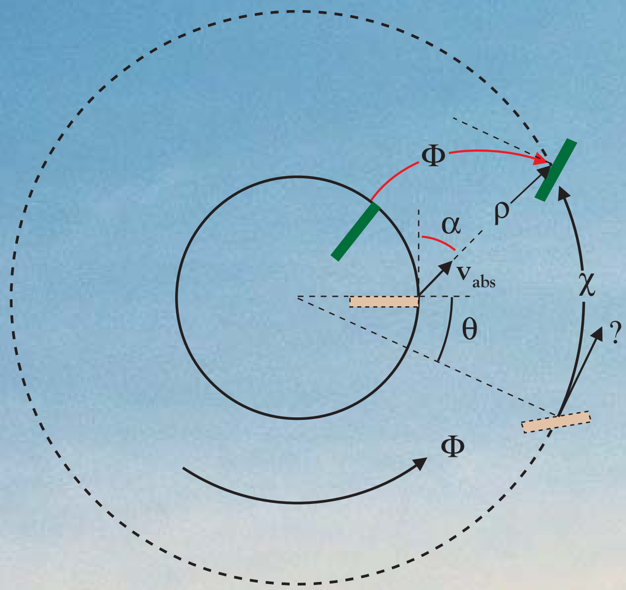
SYNSIDE

SUDDEN IMPACT

PROPOSAL FOR A NEW METHOD FOR TESTING IMPACT RESPONSE

Sudden Impact has been published in the December 2006 issue of
Aerospace Testing International (pp 82 -85),
here published with further illustrations. This article can be downloaded as PDF.

The author would like to thank Mr. Dieter Bohrmann, the owner of Synside, for making this study possible.



This article, some 3500 words, is an abstract of a longer study (some 25,000 words and about 100 illustrations) that will be published on these pages around May 2007. The study will also contain all references, illustrations and notes. When you are interested in this study please leave your e-mail, than you will be informed when it is available for download as PDF.

The author very much appreciates any comments and questions.

Please contact me at: zanden@mac.com

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Executive summary

With impact at high velocity we are often pushing the boundaries of what is physical possible with materials. However, impact response at high velocity is an extremely complicated issue and is not well understood. Impact strength is not a recognized material property. What we do know is that different materials respond differently to impact under different conditions. Therefore, with impact assessment, results from experiment should be conclusive, but we rely heavily on modeling. The reason for this is – bizarre at it may sound – that we have no suitable method available to test and research impact response at high velocity. Over the years, impact science has become largely a theoretical affair. The computer models can, however, not be accurately compared with physical results. This is a mayor safety concern.

With no proper test method available we rely heavily on accident investigation, and many accidents happened. The Concorde crashed because of the impact of a piece of rubber and the Space Shuttle Columbia because of the impact of a piece of foam. These accidents could have been avoided, when more had been known about the impact response of the materials involved, as will be discussed in more detail. After the accident critical parts of the Concorde were modified and the plane was declared air worthy again and re-certified, but not thoroughly tested for impact response. NASA started a Return to Flight Program that included one of the most extensive impact testing programs ever performed, which is still ongoing. Much has been improved but the Shuttle's safe flying status is still being questioned and intensive inspection and possible repair is now being performed while in orbit.

The lack of a good test method hampers research into the development of more impact resistant materials. The use of composites in aircraft construction took an enormous leap

Concorde

Launch Space Shuttle Columbia on the 18th of February 2003

Airbus A380
25% composite

Boeing 787 Dream liner
50% composite

Airbus A350 XWB
large scale use of composites

On the 6th of March 2006 Air Transat flight 961 was cruising at 30.000 ft above the Florida Keys when suddenly a deafening bang echoed through the packed Airbus A310-300. It appeared later that the composite rudder had snapped off. The pilots managed to land safely in Cuba, but it was the narrowest of escapes.

The airbus A300, American flight 587, lost its composite tail, shortly after take-off and crashed in the New York borough of Queens on the 12th of November 2001, killing 260 people on board and five on the ground. This accident was officially blamed to aggressively swinging the rudder by the pilot.

On the 27th of November 2005, in a hangar in Memphis, Tennessee, engineers were carrying out routine maintenance on a Federal Express A300-600, and accidentally bashed its carbon composite rudder. When the engineers took a careful look to see if the blow had done any serious harm they could hardly believe their eyes. Hydraulic fluid from the plane's control system had somehow seeped into the material and attacked the composite rudder. Its sandwich structure was coming apart. Subsequent pressure tests showed that, in flight, the whole thing could have disintegrated at any moment.

in the last few years. They make up more than 50% of the primary structure of airplanes like the Boeing's 787 and Airbus A350 XWB; some 25% for the A380. These are relative new materials and it is crucial that we recognize their limitations, impact response at high velocity in particular. There have already been very serious warning signs with composites involving Airbus.

Other industrial activities that would benefit when a better test method becomes available include comminution, excavation and drilling. The crushing and grinding for the production of some 40 billion tones of materials like stones, ores, minerals, cement clinker and coal consume not only some 6% of the world electricity production but also huge amounts of wear materials. The same applies to excavation and drilling activities. These are multi billion dollar industries and enormous savings could be made when we knew more about impact response of materials for the development of more impact resistant wear parts.

A new simple method is proposed that makes it possible to test and study impact response of materials in more detail, including the affect of impact conditions. We estimate that with this method impact velocities can be obtained from as low as 10 m/s up to at least 1000 m/s, or Mach 3, which velocity is adjustable in a continuous way or step-wise. Testing is easy, can be quickly repeated and reproducibility is excellent. The method is eminently suitable for testing composites.

Fatal impact

In many applications, impact response of materials is a critical property in that materials have to be able to safely protect us when impact occurs, for example in a car accident. Impact resistant materials play also an important role with many industrial applications, such as drilling and comminution and for military equipment. The problem with impact is that no suitable test method is available to test impact response of materials at high velocity, that is, to measure such properties as impact behavior, impact resistance, impact tolerance and impact strength. This is a mayor safety issue. For example various types of composites, which are now widely going to be used for aircraft - like the Airbus 380 and Boeing's 787 Dream Liner - cannot be tested thoroughly for impact response at high velocity.

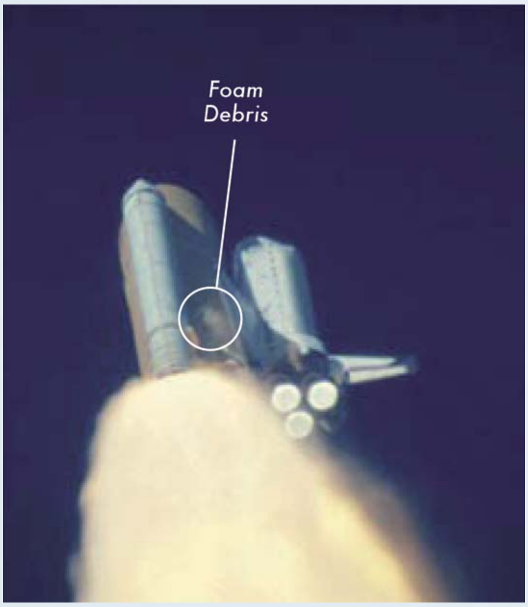
With no proper test method available we rely heavily on accident investigation. For example the automobile industry has gained enormous know-how from accidents, in particular during such races as Formulae One and Indy

Air France Concorde flight 459 crashed in Paris on the 25th of July 2000 shortly after take off because a piece of metal laying on the runway shredded a tire and a piece of rubber impacted one of the fuel tanks and ignited the leaking kerosene, killing all 119 passengers and crew, and four on the ground.

Car where materials - including composites - are tested to the absolute limits of their performance, however far too often with fatal consequences. But this led to safer cars and in a similar way, also after many tragic accidents, airplanes have become increasingly safer.

Therefore, nobody boarding Air France Concorde flight 459 in Paris on the 25th of July 2000 could have imagined - Concorde had till then the reputation to be the safest working passenger airliner in the world - that a piece of metal laying on the runway would have such dramatic affect when it shredded a tire and a piece of rubber impacted one of the fuel tanks Also the astronauts boarding Space Shuttle Columbia flight ST-107 on the 16th of January 2003 had no idea that their flight would end in disaster on the 1st of February because of a known impact of a large piece of foam that broke loose from the External Fuel Tank shortly after take off and damaged one of the composite reinforced carbon-carbon panels of the Thermal Protection System. Also with composites, there have recently been very serious warning signs involving Airbus.

Why did nobody foresee that an impact of a piece of rubber and a piece of foam could have such devastating consequences. As is often the case, after the accident the problems were solved, one way or the other. Concorde's Return to Service Program took some fifteen months of hard work, but the most important modifications were relatively simple, among them Kevlar lining in the fuel tanks, armor plating of some electrical cabling and burst-resistant tires specially developed by Michelin. Rubber projectiles were fired at a Kevlar-strengthened tank, which created holes, but these were 'only big enough to release a mere one liter of kerosene per second'. It was then concluded that this should cause no fire risk and the plane was declared air worthy again and re-certified, but it is still not known what caused the leaking fuel to ignite during the accident -"Although the engineers could



During the launch of the Columbia on the 18th of February 2003, imagery became available of a heavy foam impact to the left wing 81,9 seconds after launch when traveling at Mach 2,46 at about 65,700 feet, which caused the flight to end in disaster on the 1st of February 2003.

not be 100% certain, they felt that their best educated estimate was that the ignition was caused by a spark from arcing in the landing gear brake cabling. It was proposed that this would be armored in the remaining aircraft". After a two-and-a-half year Return to Flight Program the Space Shuttle is back in service. Much has been improved but its safe flying status is still being questioned and intensive inspection and possible repair is now being performed in orbit.

In hindsight, these accidents did not come as a surprise. Both the Concorde and the Space Shuttle had a long history of problems. With the Concorde 57 accidents happened involving a busted tire during the period 1976 to 2000, of which 32 caused serious damage to the plane, including 6 times a perforation of the fuel tank, once all the way through the wing. During the period 1981 to 2003 Space Shuttles made 112 flights. Tiles came back damaged every time and of the 79 flights imagery was available, foam shed 70 times! With the Columbia quite dramatic pictures became available of the foam impact during take off and an object was seen via military radar floating from Columbia during the second day of the mission, but this recording was not discovered until after the accident.

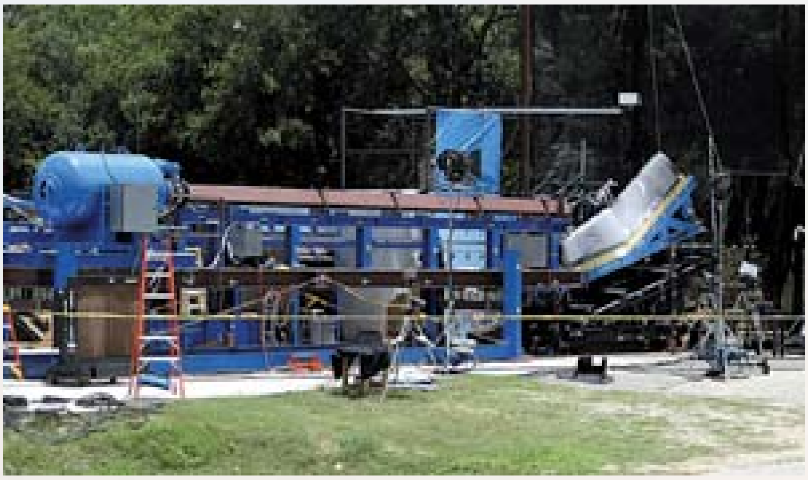
Air France Concorde flight 101 on the 14th of June 1979, that blew two tyres on the left hand main gear while taking off from Washington which caused perforation of the fuel tank, all the way through the wing. The gear could not be retracted, so the crew elected to return to Washington. Some circuitry was damaged after having been hit by debris from the tires. Debris also caused a fuel and hydraulic leak.

Much has been written about why the alarm bells were not ringing at a much earlier stage. Did engineers got used to the problems and did managers convince themselves there was no safety of flight issue, as is suggested in so many analyses. It is now thought there is another important contributing factor: we are not familiar with impact response at higher velocity. Engineers from NASA reported later that "Little was known at the time of the accident about the impact characteristics of either the foam isolating the external fuel tanks or the reinforced carbon-carbon thermal protection system", and consequently nobody could draw any sensible conclusion when the pictures became available.

NASA's Return to Flight Program

Being not familiar with a problem often leads to either more or less ignoring it or take refuge in theoretical modeling. Often insufficient data can be made available for both the proper development and the running of such models, and this is certainly true for impact, as NASA learned the hard way when modeling during the flight suggested that most probably no serious damage had occurred during the foam impact.

Immediately after the accident NASA started a Return to Flight Program that included one of the most extensive impact testing programs ever performed. First a full-scale test was performed that simulated the actual impact. It was not too difficult to shoot a larger piece of foam at the estimated relative velocity (777 ft/s or 237 m/s) and at the estimated angle of incidence (25.1^{0}) with correction for self rotation) against the leading edge where the actual impact was thought to have occurred:
"I don't think anyone expected to see a 16-inch square hole", one of the engineers reported later, "In the blink of an eye, there it was, and hundreds of people immediately came to terms with how much damage a piece of foam can do"

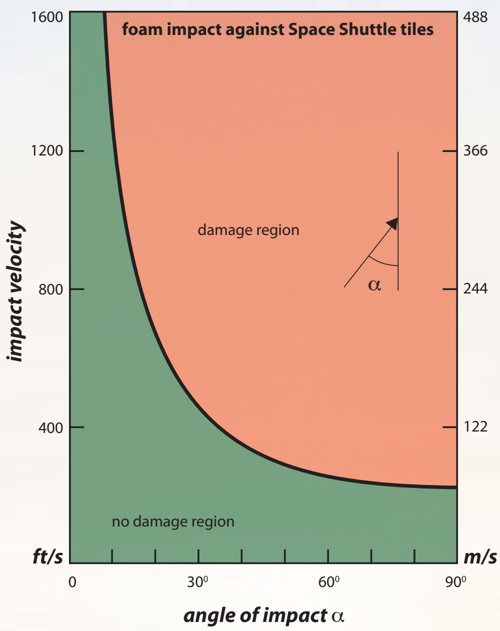


Base on physical evidence the Columbia Accident Investigation Board (CAIB) concluded that the left wing of the Orbiter was struck in the vicinity of the lower half of the number 8 reinforced carbon-carbon panel by a large irregular shaped piece of foam that separated from the left bipop ramp of the External Tank. This is here simulated with an 1:1 test with the impact of a rectangular 19"x11.5"x5.5" block weighing 1,67 lbs (0,76 kg), at an estimated 777 ft/s (237 m/s), at the estimated angle of incidence of 26.1 degrees, at the estimated clocking-angle (300) and was self-rotating at an estimated 18 Hz. It was not possible to simulate this self-rotation during the full-scale test and this was modeled to be compensated by a five-degree increase in angle included in the 26.1 degrees at which the foam hit the test panel. The impact created a hole roughly 16 inches by 17 inches.

"I don't think anyone expected to see a 16-inch square hole", one of the engineers reported later, "In the blink of an eye, there it was, and hundreds of people immediately came to terms with how much damage a piece of foam can do".

It soon became clear that it was much more difficult to study the impact of foam, ice and ablator materials against reinforced carbon-carbon panels and ceramic tiles in more detail, with only limited experience. "I was amazed that a 2-gram piece of foam could break a reinforced carbon-carbon strip", an engineer reported later, and with results from previous tests incomplete, NASA engineers had to essentially start from scratch. The impact characteristics of the materials were investigated in great detail and most interesting analytical models were developed.

Impact power increases with velocity and at more steep angles, but the level at which damage occurs is also strongly influenced by the deformation characteristics of the materials involved, impactor configuration, impact face curvature and self-movement of the impact partners. For foam impact against the tiles a theoretical critical curve was drawn with angles and velocities below which no damage is supposed to occur ***(figure 1)***. The curve, which is pivotal for large scale numerical simulation, "agreed extremely well" with test results, but the numbers were insufficient to draw firm conclusions. A special pressure gun with a square barrel was used to shoot rectangular impactors. Flat and elongated sharp edged configurations, like metal debris, broken glass or ice and even foam, cause much more damage then rectangular shapes. These cannot, however, be accelerated with a pressure gun and it is extremely difficult, if not impossible, to include such configurations in computer models, and had to be ignored. Due to lack of detailed damage information as well as material properties, it was decided to model the impact against the thin curved RCC panels and an analytical boundary condition was developed for rectangular foam impact.
Impact tests took place against stationary surfaces, which in reality are moving at high velocity. Theory tells us that this does not matter, as long as static impact takes place at the same 'relative normal velocity and angle'. But what about a fast accelerating test article, that is hit by a rapidly self-rotating impactor, in case of the Columbia with an estimated 18 revolutions per second? Controled self-rotation cannot be generated with a pressure gun, but simulations indicated that this dramatically increases impact power and can cause damage at much flatter angles of impact. For the tiles this affect was compensated for with non-rotating impact tests under modeled conditions, essentially at a larger angle of impact, that were assumed to produce similar damage than rotating rectangular impact. For the panels modeling indicated



These are the results of modeling the trajectory of the piece of foam that broke loose, to determine the likely position and velocity histories of the foam. According to the models impact took place at an estimated 777 ft/s, at 20.1° and with 18 Hz self rotation.

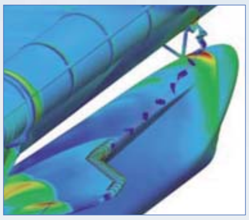


Figure 1 Impact damage and no-damage regions
Theoretical damage and no-damage regions for foam impact against the tiles of the Space Shuttle, as demarcated by impact velocity and angle of impact.

(From figure 17 Columbia Accident Investigation Board, Volume II, Appendix D.12, submitted by James D.Walker)

Observing a rotating garden sprinkler through the eyes of Einstein

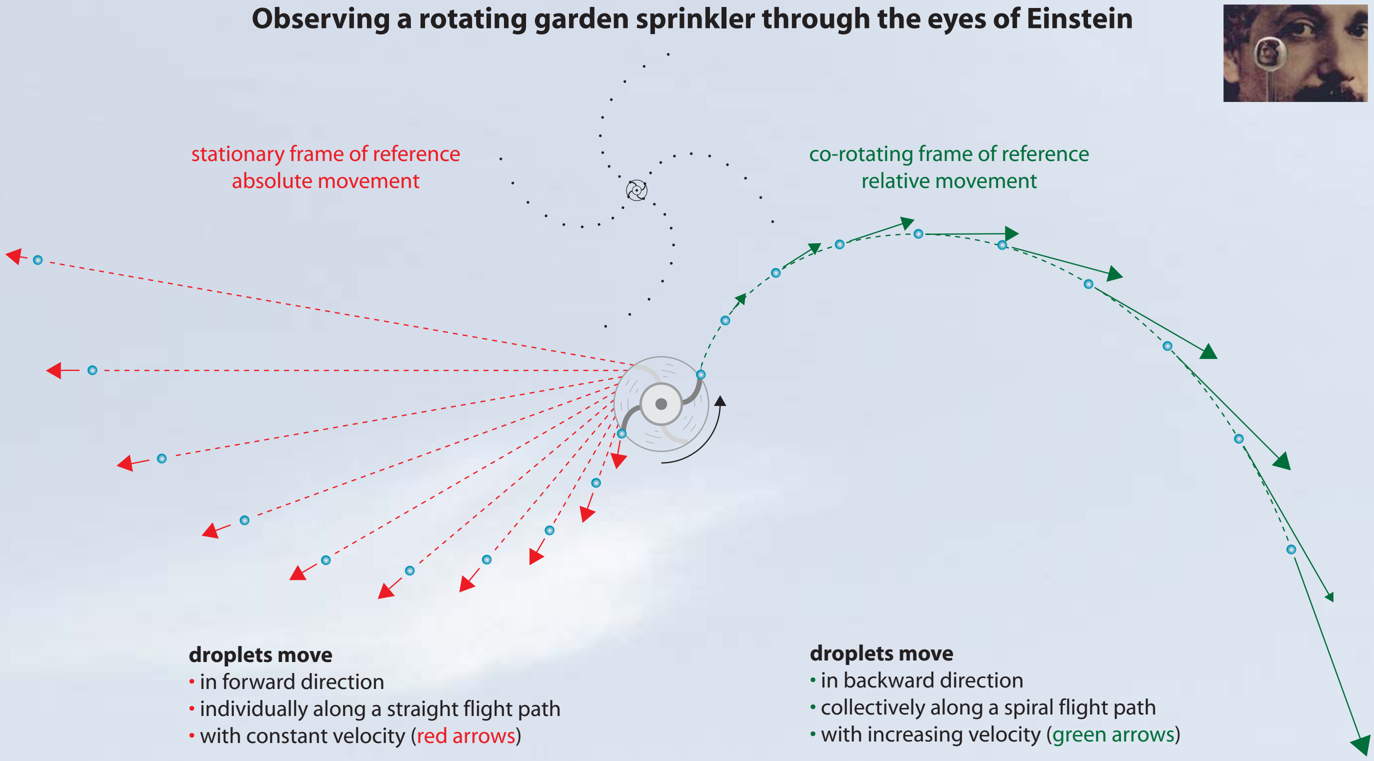


Figure 2 Movement droplets thrown from a garden sprinkler observed through the eyes of Einstein
Seen from a stationary frame of reference each of the droplets moves individually outwards; that is, each along its own straight flight path in a forward direction with constant velocity (red arrows). However, seen from a frame of reference moving with the sprinkler the particles move behind each other along a co-rotating spiral flight path in backward direction; and we notice that the distance between the droplets increases progressively along this spiral, which means that the droplets accelerate (green arrows).

that an increase of the angle "by roughly 5^0", compensates for 18 Hz rotation. This is of course largely a conjectural approach, but it provides a safety margin.
Self-rotation and acceleration do influence rebound behavior which can cause secondary damage and fast moving surfaces can become severely strained, which reduces impact resistance. Double impact causes material to break at significant lower velocities but this can neither be achieved with the pressure gun nor modeled because this phenomenon is not yet understood. Surprisingly not too much attention has been paid to thermal variation, which is known to have a mayor influence on impact resistance, although tests were performed at both room and cryogenic temperatures. The engineers managed to create semi-vacuum impact conditions, but research was not conclusive whether this really influences impact response.

Notwithstanding these shortcomings, the engineers did an impressive job - bravo - impact response has never been studied in such debt before and enormous progress has been made. However, impact response is a very complicated issue, certainly so for the materials involved. It is recognized that the foam, tile and panel materials are very difficult to characterize for combined impact-thermal resistance. Based on the material available to us – with so much reliance on modeling, with so many important impact conditions that could not be included in the test program and the models, limited physical verification and a strong focus on the accident conditions, it has to be questioned to what extend the analysis prediction capacity is now capable to accurate model events on the space shuttle, in particular under conditions other than during the Columbia accident. But the program is still ongoing and with debris liberation and possible impact damage accurately monitored during launch, accurate damage assessment, continuous improvements and development of more resistant materials and last but not least inspection, testing and possible repair in space, we are positive that a similar accident is not likely to happen again.

Proposed test method

With impact the boundaries are pushed very far of what is physical possible and here only the experiment is conclusive. The problem engineers are facing is that they have no suitable method to their disposal to study and test impact response in more detail at higher velocity, which appears to be very different from that at lower velocity. Impact science is largely a theoretical affair and relies heavily on modeling. This hampers the development of more impact resistant materials. To make progress in this field we are in urgent need for a method that measures impact strength, which is arguably one of the most important but least understood material properties. It is important to be able to direct a stream of impactors with great precision and with controled frequency towards an impacting surface, something like a laser, a water jet, a machine gun or a high frequency oscillator. For most purposes these principles are not suitable. Air pressure can only be used when very small particles are involved. It is actually very difficult to accelerate a controled stream of coarser impactors with different sizes and different shapes. It was therefore quite a surprise that all this can actually be achieved in an astonishing simple way. This became apparent after the study of the movement of particles in a rotating system for the development of a new crusher - the SynchroCrusher - which is now proven technology. Imagine taking a close look at the movement of water droplets thrown from a rotating garden sprinkler using one of Einstein's basic principles ***(figure 2)***. From a stationary frame of reference we see that each of the droplets moves individually outwards; that is, each along its own straight flight path in a forward direction with constant velocity. However, seen from a frame of reference moving with the sprinkler the particles move behind each other along a co-rotating spiral flight path in backward direction; and we notice that the distance between the droplets increases progressively along this spiral, which means that the droplets accelerate. Now comes the big surprise: When you increase the water pressure by further opening the tap you observe that the sprinkler starts to rotate faster and covers a larger area, but, contrary to intuition, the co-rotating spirals do not bend outwards but stay in the same position: the spirals only become longer and the droplets move faster. Now think of a rotor that is provided with impellers, which accelerate particles in a way similar to the droplets. When a test article is installed on the rotor at greater radial distance, such that its impact face is transversely directed to the co-rotating spiral stream, an 'ideal' co-rotating impact test device that fulfills virtually all conditions has suddenly been created ***(figure 3)***.

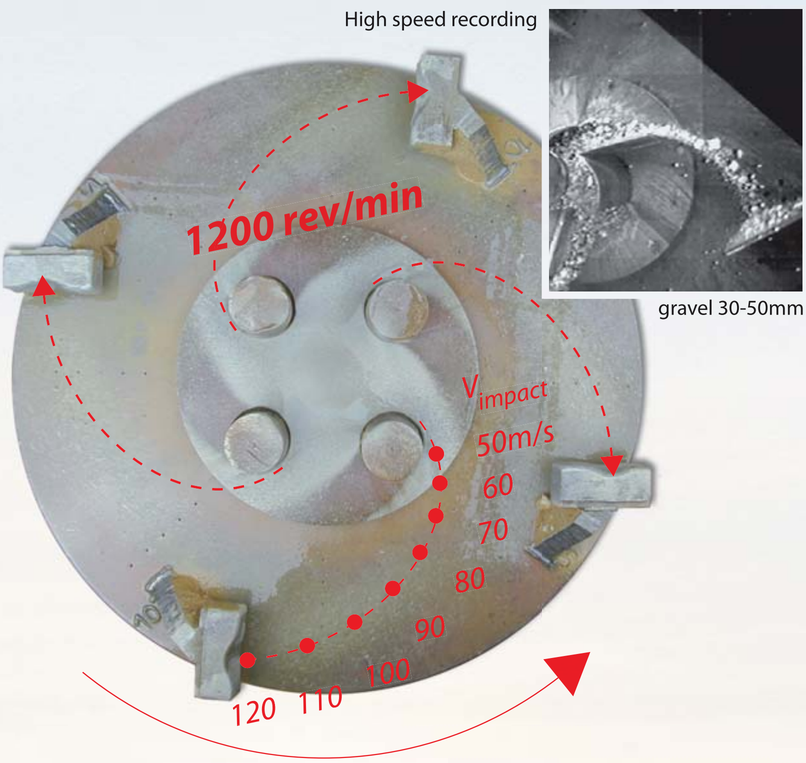


Figure 3 Rotor
Rotor with impellers for accelerating particles along a co-rotating spiral flight path, for impact against a plate that is positioned transversally to the spiral stream.

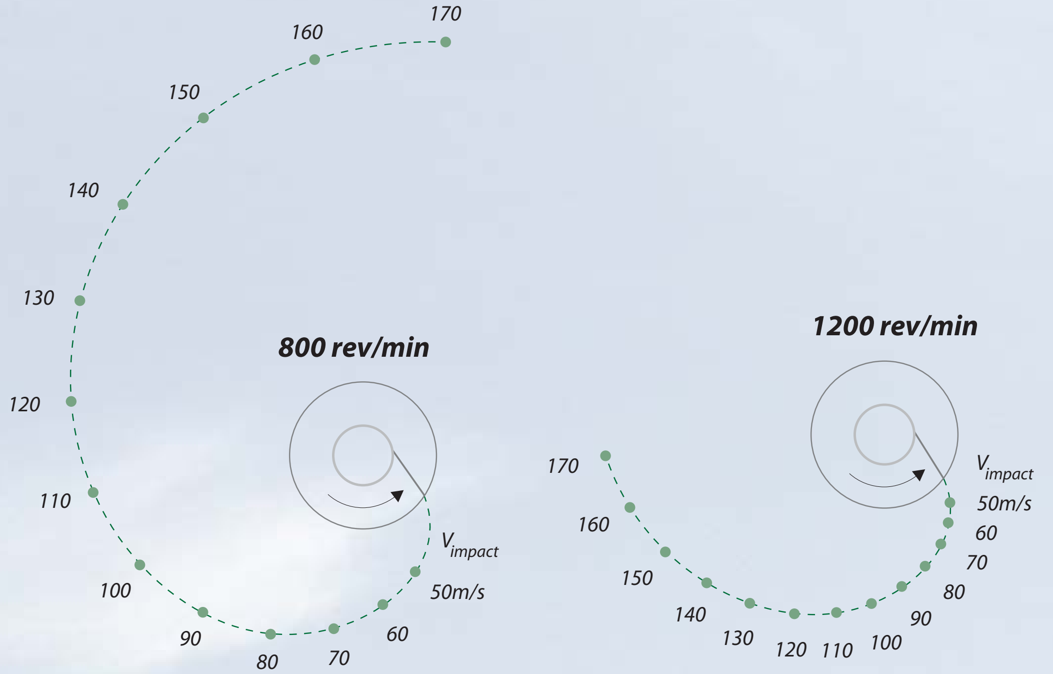


Figure 4 Impact velocity as determined by rotational velocity and radial distance
The impactor accelerates along the co-rotating spiral, here with the rotor rotating at 800 and 1200 revolutions per minute. The location for impact at a certain velocity can be chosen.

Impact velocity can be accurately chosen and adjusted with the aid of both rotational velocity and radial distance ***(figure 4)***. Impact position and angle of impact can be carefully selected. Both single, double and multiple impact can be achieved with controled frequency with the aid of a launching devise. This makes it possible to define an intrinsic impact strength value, in a way similar to the concepts of compressive and tensile strength; that is, by steps or gradually increasing impact velocity during repetitive impact.
Testing is easy, can be quickly repeated and reproducibility is excellent ***(figure 5)***. It is estimated that impact velocity can be increased from as low as 10 m/s to up to at least 1000 m/s, or Mach 3. To reach higher impact velocity, the impacting face has to pass, often several times, in front of the approaching impactor before impact takes place, making that the co-rotating spiral virtually spirals outwards around the axis of rotation ***(figure 6)***. Impactors of virtually any shape can be accelerated and sizes of both test article and impactor can be varied within wide ranges. Controled impactor self-rotation can be obtained, by making either the impactor or the test article to rotate with predetermined velocity before it is released. In a similar way the test article can be made to rotate for self-rotating impact. Linear acceleration and de-acceleration can be simulated with rotor-speed. Since the position of the co-rotating spiral is fixed, the rotor can be provided with an open or closed spiral tube through which the impactor accelerates without touching the tube surfaces, whatever the rotational velocity. It is also possible to provide the rotor with a spiral rail and some kind of carriage device, such that the position of the impactor can be orientated exactly for impact. Still, semi-vacuum conditions might be required for very high velocities, especially with very light impactors like small pieces of foam. Centrifugal force can be used to generate stress within the test article. By placing the rotor in a closed chamber, temperature and air pressure can be regulated. The impact surface can be covered with an ice layer, but also be made red-hot. Dust and sand storm, rain and hail can be realistically simulated.

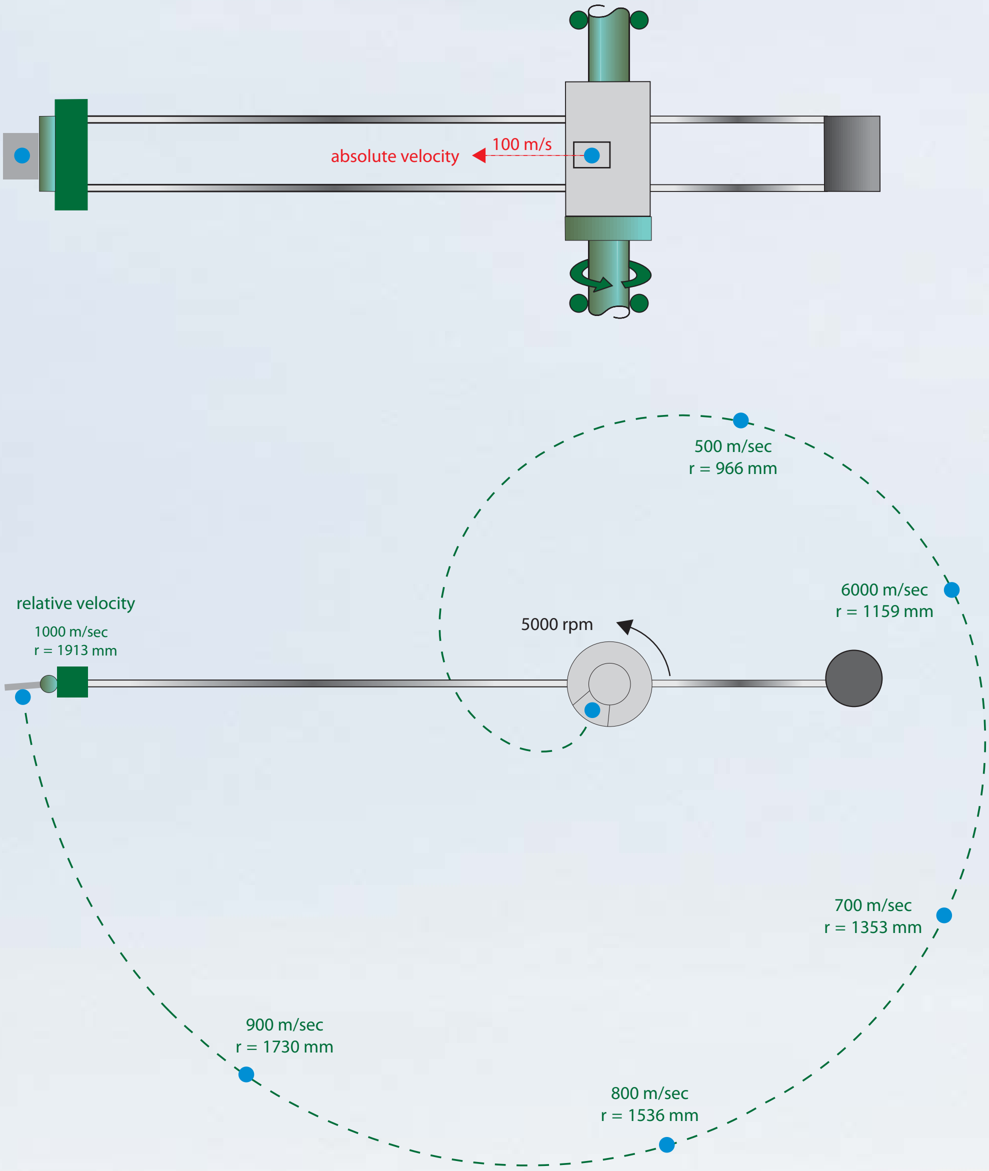


Figure 5
Possible test rotor
Rotating impact test apparatus for centrifugal launching an impactor with an absolute velocity of some 100 m/s, which then accelerates along the co-rotating flight path for impact against a test article at a relative velocity of some 1000 m/s. The device is here provided with separate launch and impact platforms each equipped with balance elements. The platforms are made out of lightweight composites and are connected to the shaft with high strength synthetic cables. The axis has bearings on both sides. The most difficult part to construct is the device that releases the impactors(s) when the rotor has reached the intended rotational velocity.

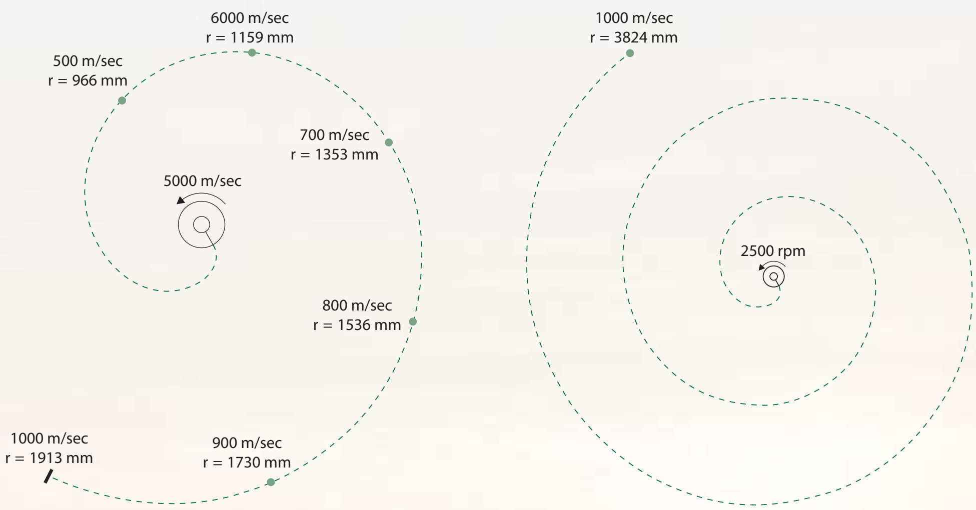


Figure 6 Spirals for impact at 1000 m/s
To reach higher impact velocities, the impacting face has to pass, often several times, in front of the approaching impactor before impact takes place, virtually spiraling outwards around the axis of rotation. Here an impact velocity of 1000 m/s is obtained at a radial distance of 1913 mm at 5000 rev/s and at 3824 mm at 2500 m/s.

Applications

The method is unique in that it is possible to direct a stream or cloud of impactors accurately for impact with controled frequency at a velocity increasing from as low as 10 m/s up to more than 1000 m/s. This way the impactor or the impact article can be loaded until disintegration takes place. Applications include research purposes, measuring impact strength and hardness, the development of more impact resistant materials, quality control, simulation of accident conditions and to validate modeling. The test method is eminently suitable for testing lightweight materials, composites in particular.

Many of the impact tests performed by NASA could have been performed in a more realistic way with co-rotating impact and numerous other applications can be envisaged. For example composites, which are going to be used for the A380 and the Boeing 787, become vulnerable under stress and their impact resistance is strongly influenced by temperature. With the available methods it is not possible to test these materials thoroughly for impact and how this influences fiber shearing, delaminating and tearing, which is a mayor safety issue. The method is also perfectly suited for testing vanes, in that both impact and secondary sliding can be simulated simultaneously.

Concluding remark

The proposed test method possesses a number of unique features. The device is of simple construction, testing is easy, can be quickly repeated and reproducibility is excellent. With an impact velocities range of 10 to 1000 m/s, the method covers virtually all impact conditions materials can experience in day-to-day practice. Higher velocities are probably possible, but therefore one has first to recognize whether this is of practical interest, that is, whether there are applications in the 1000 to 10,000 m/s plus range. Space dust impact is such an application. Here small sizes are involved and extremely high rotational velocity can be achieved, but this is not within the scope of the present study.

Undoubtedly, it will appear that there are also shortcomings and limitations - it is not possible to measure deformation behavior - but we expect that important improvements can be made. Ideas create ideas. No doubt, when available, such test facility will contribute to a better understanding of material impact response. The development of the testing device is not an easy task, but it can be done.
It requires great precision and the configuration must be easy adjustable, that is the position of the impact platform relative to the launching platform.

Back in 1997 we faced a very critical industry when we introduced co-rotating impact for comminution purposes, that is, for crushing down gravel from some 80 mm down to 10-15 mm. It soon became clear that this so-called SynchroCrusher produced a superior quality crushed product. The new crusher provides a level of performance customers really require – but which is very difficult or impossible to achieve with machines available now. But we had to overcome many problems. So were existing wear parts not strong enough to withstand the combined loading of the high centrifugal force (some 100 kN) and that of the heavy repetitive loading, generated by the impacts of a continuous stream of 100 mm (1,5 kg) gravel particles at some 100 m/s.
It took about three years to develop completely new types of reinforced bi-metal cast wear parts. But in the end we succeeded and we are convinced this is also possible with the proposed test method.

For more information on the SynchroCrusher please browse this site that contains a wealth of information including unique high-speed imagery of the co-rotating spiral movement and impact for comminution purposes.

Through this site you can also contact us when you are interested in the further development of this test method, for which a patent has been issued and other patents apply.

An interesting question remains why this co-rotating spiral was not used at an earlier stage for this purpose. The reason is probably that such a co-rotating spiral (this probably also applies to spiral galaxies if not cosmos as a whole), is not well known because it cannot be described with a mathematical formulae, such as the Archimedes and the Logaritmic spirals. The position of the co-rotating spiral has to be calculated by translation of the straight flight path. This is somewhat complicated and is explained in some detail in US 5,860,605. A computer simulation program is available to simulate absolute and relative movements of particles in the rotating system discussed here.

To be or not to be a Spiral...

Whirlpool Galaxy M51
Hubble Heritage