A98-31595

ICAS-98-R,4,5

DYNAMIC SEAT TESTING AND HEAD INJURY CRITERIA – AN AIRCRAFT MANUFACTURER'S EXPERIENCE AND A VIEW ON THE FUTURE

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Abstract

This paper presents the procedures and methods applied in the crashworthiness certification testing of the PILATUS PC-12 crew and passenger seats. The problems encountered in the Head Injury Criteria (HIC) component testing have shown that it can not replace the more expensive full scale testing, but is still useful for development testing and for reducing the number of full-scale tests. Especially the simulation of complicated impact situations with the currently available test devices and the correlation with full-scale test results is difficult.

The crashworthiness requirements in FAR 23.526 have resulted in considerably higher certification costs compared with the old 9-g seats. At the same time, however, the PC-12 customers want a high degree of cabin layout flexibility. In order to offer cabin flexibility at low costs HIC related parameters must be defined in the seat specification. In addition a certification procedure should be applied, in which component testing is used for locating critical impact situations for the seat design and for selecting the critical impact situations for HIC full-scale testing. In this way a large number of possible cabin layouts can be analysed and certified, whereas only a few HIC full scale tests will be required

Introduction

Since 1988 the new crashworthiness requirements of FAR 23.562 [1] have forced the aircraft manufacturers to pay more attention to their crew and passenger seats. Although the dynamic seat testing and HIC requirements are about ten years old, aircraft and seat manufacturers are still struggling to comply with these regulations.

In that respect PILATUS Aircraft Ltd. was not an exception when certification of the seats for the PC-12 was started. However, PILATUS Aircraft Ltd. has gained extensive experience during the test series performed to comply with the crashworthiness requirements. The result of these tests is that the PC-12 is one of the few newly developed aircraft that offer multiple cabin layouts, which fulfil the latest requirements. The solutions that have been developed, and will be developed in the future, allow for customisation of the interior layout, number of seats and seat configuration (multiple options). Based on the experience gained during the certification of the PC-12 seats and interior, PILATUS Aircraft Ltd. is now able to define the specifications that the interior and seats have to fulfil to achieve certification successfully, and offer maximum freedom to comply with customer wishes without re-testing.

The first part of this paper describes the procedures and methods PILATUS Aircraft Ltd. has used to comply with the dynamic seat requirements of FAR 23.562. In particular the problems that arose from the component testing are discussed in detail. Based on the experiences gained during the certification process, the determining parameters for the seat design and certification, with respect to both seat structural integrity and HIC, have been identified. In the second part of this paper these parameters are discussed and general rules for the seat design are defined. Also a procedure, which combines component and full scale testing in order to recognise the relevant problems early in the certification program and in order to minimise the test costs, is presented.

The dynamic seat and HIC testing program for the PC-12: certification philosophy and procedures

At the beginning of the certification program of the PC-12 crew and passenger seats PILATUS Aircraft Ltd. decided to use mainly component HIC testing to show compliance with the HIC requirements in FAR 23.562. This decision was based on results with a pendulum head impactor at the Federal Technical University (ETH) in Zürich [2]. The main reason for this decision was to limit the costs of the test program and, at the same time, be able to cover the defined range of yaw angles combined with occupant sizes ranging from a 5th percentile to a 95th percentile occupant. This has lead to the following procedure for the seat testing and HIC certification program:

1. Dynamic seat testing of the crew and passenger seats without other interior items such as bulkheads, sidewall panels or other seats.
2. Digitisation of the head trajectory from the dynamic tests and the construction of head trajectories for 5th and 95th percentile occupants.
3. Determination of the impact area for occupant sizes ranging from 5th percentile female to a 95th percentile male combined with a yaw angle ranging from -10° till +10° either side of the direction of flight.
4. Component HIC testing of the critical impact locations.
5. Full scale HIC testing of a few impact locations in order to verify the component test results.

21st ICAS Congress
13-18 September 1998
Melbourne, Australia

In the following sections these steps are described in more detail and the problems encountered and applied solutions are discussed.

Dynamic seat testing of the crew and passenger seats

The aim of the testing was to show structural integrity of the seats under the test conditions defined in FAR 23.562. The testing has shown that each of the two test conditions has its own critical test requirements. In the case of the horizontal (21g) test the strength of the seat is the critical item, whereas for the vertical test (15 g) the maximum allowable lumbar load is the most difficult criterion to fulfil.

Determination of the head trajectories for all occupant sizes

The dynamic tests are performed with a 50th percentile Anthropomorphic Test Dummy (ATD), but as a range of occupant sizes must be considered [(3)], head trajectories have been derived for the 5th percentile female occupant and the 95th percentile male occupant. This has been done by constructing head trajectories, which are offset from the 50th percentile male occupant. The value for the offset has been taken equal to the difference in the distance between the hip rotation point and the eye for the different occupant sizes (see Fig. 1). Although this method does not consider the influence of the dummy weight on the head trajectory (the difference in dummy weight will cause different structural deformations), it will be more realistic than the simplified impact area procedure presented in [(3)], and does not necessarily require more testing.

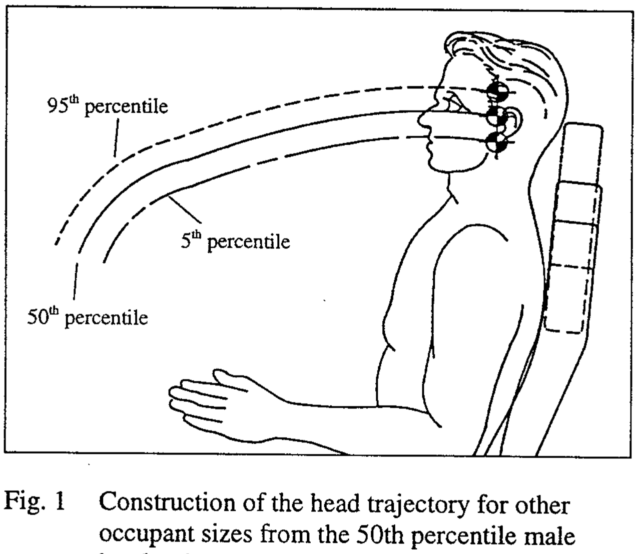

Fig. 1 Construction of the head trajectory for other occupant sizes from the 50th percentile male head trajectory.

Determination of the impact area for all occupant sizes and yaw angles

Using the head trajectories for the three occupant sizes and considering the range of yaw angles from -10° to +10°, the impact areas have been determined using a CAD model of the cockpit and cabin. A sphere with 100 mm radius has represented the occupant head. Together with the impact location on the interior item, also impact velocity and the direction of the impact (angle between velocity vector and a suitable reference plane) at the first point of contact have been determined. The velocity for the 50th percentile can be taken from the digitisation data, whereas in the case of the 5th and 95th percentile occupants the location of the head at impact is related to a point on the 50th percentile head trajectory as shown in Fig. 2. Referring to the difference in the structural deformation between the different occupant sizes, it is clear that in this way the velocity for the 95th percentile male occupant is optimistic, whereas the velocity for the 5th percentile female occupant is conservative. The same problem occurs with the simplified method in [(3)], and it can only be solved if dynamic seat tests with the different ATD sizes are done, which is prohibitively expensive.

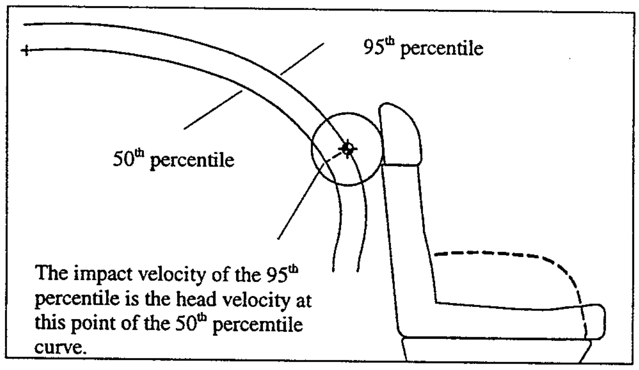

Fig. 2 Determination of the impact velocity for other occupant sizes than a 50th percentile male.

Component HIC testing of the critical impact locations.

In order to reduce the amount of component testing critical impact locations have been defined based on the following criteria:

- The impact velocity.
- The angle between the velocity vector and the plane of impact under consideration of the direction of the highest overall stiffness of the impacted structure.
- The local shape and stiffness of the impacted structure.

Subsequent to the definition of the critical impact locations the component HIC tests have been performed for the crew and passenger seats and problem areas have been defined. This has lead to further component testing and final verification by full-scale testing.

Full scale HIC testing of a few impact locations in order to verify the component test results.

Finally a total of three full scale HIC tests have been performed to show compliance for the most critical and complicated impact locations. The correlation between component testing and full-scale test has shown to be not only difficult, but also of limited value. Subsequent to the final testing, the component modifications have been incorporated in the production aircraft as well as in service aircraft.

The problems of the component HIC testing and test correlation

During the test series that have been performed for the certification of the PC-12 seats, it has become clear that component HIC testing can not fully replace full scale testing as a means of compliance. However, it is a very useful tool for development work and in certain cases component testing alone is sufficient to show HIC compliance. For the PC-12 HIC certification program three different component test devices have been used. Each of these test devices has its own specific (range of) impact situations for which it is most suited.

In the following sub-sections some of the results of the component testing and the problems that have been encountered during the testing and correlation are discussed. To clarify these problems, the three component test devices used are described first. The conclusions with respect to the area of application for each of the devices have been based on the experiences gained from the PC-12 test program. All these impact devices have also been used for development work for the automotive industry.

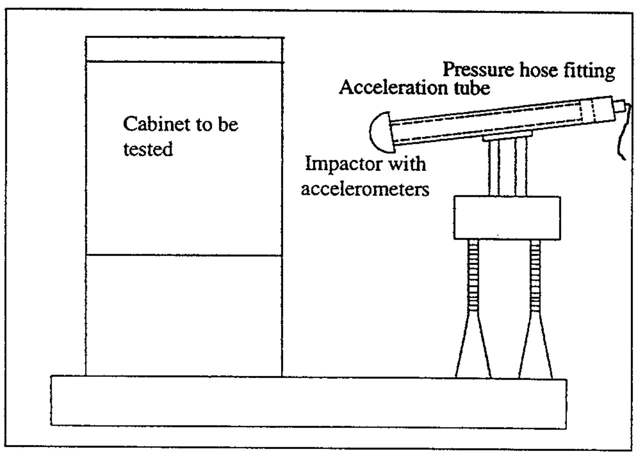

Fig. 3 Schematic picture of the linear impactor set up for impact tests on cabinet walls.

Component test devices

Linear impactor. The linear impactor consists of an aluminium tube with a half sphere mounted at the end (see Fig. 3). The total weight of the tube and the sphere equals the weight of a 50th percentile dummy head. The impactor is accelerated in a metal tube by high-pressure dry nitrogen. Depending on the distance between the acceleration tube and the point of impact, the impactor can be completely free or still partly in the acceleration tube at the moment of impact. Whether this is the case or not has a large influence on the results when sideward loads and accelerations are acting on the impactor. In general the area of application of this impactor is limited to impacts more or less normal to a flat surface (e.g. bulkheads). As the dynamic behaviour of impactor is different from the behaviour of a dummy head, the results need to be verified by full-scale test.

Pendulum head impactor. The pendulum head impactor consists of a pendulum arm to which a dummy head is mounted (see Fig. 4). The arm can be pulled up to a certain height, which determines the impact velocity. An additional weight is used to increase the maximum impact velocity possible. After the arm is released, it is stopped when it reaches its lowest point and the dummy head is disconnected from the pendulum. So the dummy head is in free flight at the moment of impact.

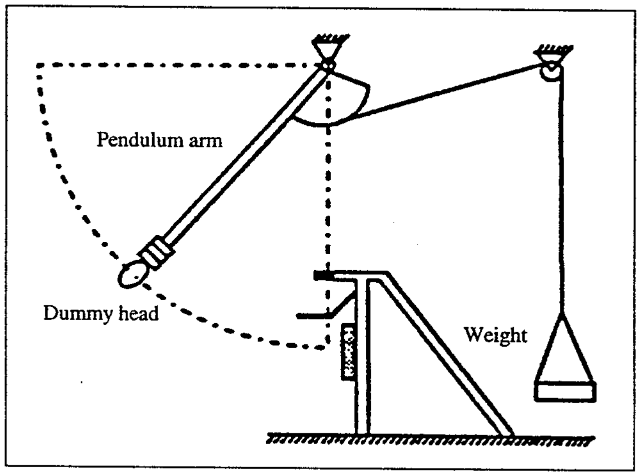

Fig. 4 Schematic picture of the pendulum head impactor.

This has the advantage that there are no interference problems between the impactor test device and the impacted structure. However, unrealistic head rotations can occur if the point of impact on the dummy head does not coincide with the intersection point of velocity vector and the outside surface of the dummy head (see Fig. 5). Also the local shape of the impacted structure around the point of impact can influence the validity of the results. So it can be concluded that this type of impactor is mostly suited for impacts on flat or smoothly shaped surfaces such as bulkheads, side wall panels and (parts of) seat backrests.

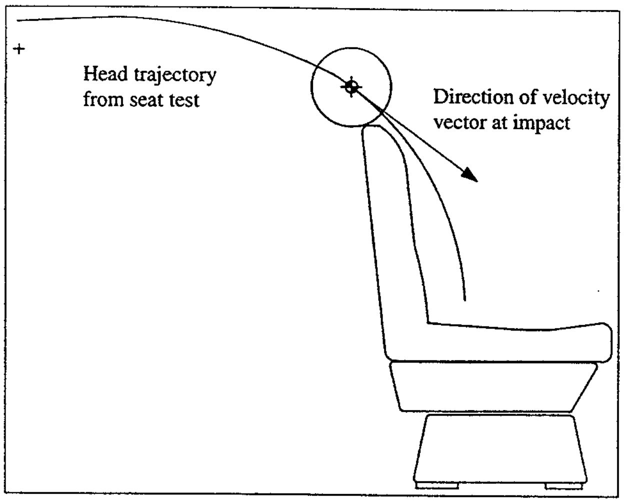

Fig. 5 An impact situation for which unrealistic head rotation occur because the velocity vector is offset from the impact point on the dummy head.

Rotational head impactor. This component HIC test device, developed by MGA Research Corporation (USA), consists of a dummy head and neck assembly connected to a rigid arm which can rotate around a fixed point (see Fig. 6). A nitrogen driven actuator accelerates the arm and the head up to the required impact velocity. A brake system is installed to decelerate the arm if its velocity is not reduced to zero by the impact.

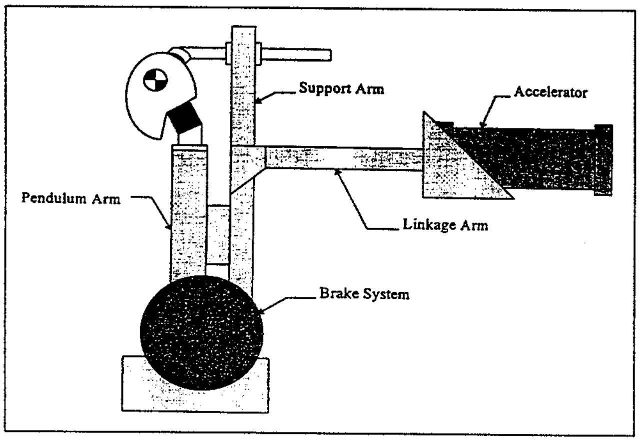

Fig. 6 Schematic picture of the rotational head impactor.

Since the dummy remains attached to the arm, no unrealistic rotations can occur when the impact location on the head is offset from the dummy head c.g. as is the case with the pendulum. Nevertheless unrealistic rearward head rotations can also occur with this impactor when the arm still moves forward whereas at the same time the dummy head velocity is already zero. This can be prevented by separately decelerating the arm shortly after head impact. However, this needs fine-tuning for more or less each specific impact situation. Realistic forward head rotations at the end of the head trajectory, which are caused by the shoulder belt in a full scale test, have been simulated on this impactor by decelerating the arm just before impact.

It can be concluded that this type of impactor can be used for a large variety of impact situations and can be fine-tuned to simulate relatively complex head movements at impact.

Problems encountered during component HIC testing for the PC-12 certification

For the PC-12 certification, component HIC tests have been performed for impacts on the glare shield, sidewall panels, seat backrest and armrest, bulkhead and lavatory cabinet wall. During these component tests with the previously described test devices, several problems have been encountered, which show the limitations of the individual devices as well as the limitations of component testing in general.

The following three impact situations will be discussed here:

1. Impact on the lavatory cabinet wall
2. Impact on the seat arm rest (opposing seats)
3. Impacts on seat backrests.

Impact on lavatory cabinet wall. For the impact on the lavatory cabinet wall a weakening pattern has been developed by component testing, using the linear impactor. The testing showed that the critical impact occurs on the sloped part of the lavatory cabinet wall. During the impact the dummy head slides along this sloped part of the wall. This movement is very difficult to simulate properly with the linear impactor, whether the impactor is still in the acceleration tube or already outside the tube at the moment of impact.

In order to show the effectiveness of this weakening of the cabinet wall a full-scale test has been performed. Although the HIC value for the component testing and the full scale testing were about the same (632 compared with 654) and also the failure of the wall was about the same (first impact), the differences occurred at the second impact on the inside of the lavatory cabinet. However, it was this second impact which has produced the above HIC values, with considerable differences in the maximum deceleration level and the width of the deceleration peak.

Impact on seat armrest The theoretical head trajectory analysis using the head trajectory from the dynamic testing of the single seat, showed impact on the armrest of the opposing seat for a club four configuration (Fig. 7) for the 10° inboard direction. As it has been expected that this would not occur in reality, a full-scale test has been performed. Indeed this test has showed that the impact on the armrest has not occurred because of the contact between the occupant legs and the lower part of the opposing seat. Consequently the impact occurred on the front part of the seat cushion, which has resulted in a HIC value of 648.

Such an impact situation is almost impossible to simulate properly by component testing. If possible, a full-scale test is required to find the right impact location, which then makes all component test unnecessary (if the HIC is below 1000).

Impact on seat backrest. One impact on the backrest of the seat in front has been tested by means of the pendulum. Verification by full scale testing has resulted in a HIC value, which is about three times higher (and well above 1000). Analysis of the full-scale test has shown that the occupant knees hit the backrest in front before the head impacts on it. As a result of the knee impact the backrest of the seat in front is already highly loaded and is also moving backwards at the moment that it is hit by the head. Consequently, the dynamic response of the seat is completely different from the seat in the component test, which is simply attached to seat rails, but not preloaded or moving.

This difference in dynamic response resulted in a much larger rebound velocity for the full-scale test and a corresponding wider head deceleration curve and higher HIC value. Again such an interaction between other occupant body parts (than the head) and the structure that is impacted by the head is very difficult to simulate by component testing. At least a full-scale test is required to know what exactly happens before any simulation can be done.

This HIC problem has been solved by a combination of an optimisation of the restraint system to improve the head trajectory and velocity and a 1" increase of the seat pitch.

Advantages and disadvantages of component HIC testing

The main advantage of component HIC testing is the considerably lower costs compared to full scale testing. Not only is the test device itself cheaper to use than a Hyge-sled or a deceleration sled, also the specimen costs per test are much lower because no seat is required for a dummy. Normally this seat can only be used once.

Another major advantage of the component HIC testing is that the exact impact location, as determined by using the CAD model of the cabin, can be tested. This is not only possible for the 50th percentile occupant impact location(s), but also for impact locations for other occupant sizes.

Furthermore component testing requires, in general, less set-up time than full-scale test, and therefore can be performed quicker.

The major problem with component testing at the moment is still to prove that the same results are obtained as with full scale testing. Besides the specific shortcomings of the currently available test devices as described in previous sections, there are also some general shortcomings which makes it difficult to properly simulate the impact situations by component testing:

- A realistic simulation of the head movement at the moment of and during the impact. The linear impactor and the pendulum provide a linear head movement, whereas the head path in reality is often curved, especially at the end of the head path (this is when most of the impacts take place). Although the rotational impactor gives a curved head path, it has a constant radius, which is not the case in reality.
- Related to the previous item is the difficulty of matching head rotations near the end of the head trajectory, which are caused by the restraint system and seat stiffness.
- Interaction between other dummy parts (than the head) with the impacted structure can influence the head trajectory and head velocity. So the impact situation in a full-scale test will be different from the impact situation obtained by using a CAD cabin model and the head trajectory from a dynamic seat test without surrounding structure. Consequently, the HIC results will also differ. Some of these situations are:
  1. Influence of the dummy shoulder in the case of impact on the cabin sidewall. In this case the contact between the dummy shoulder and the sidewall will reduce or prevent the impact of the head on the sidewall.
  2. Influence of the upper leg position. Here the obstructed forward movement of the dummy's legs can limit the forward movement of the hips and the upper body and head. This can change the head trajectory and consequently changes the impact situation. Note that in such case large loads are acting on the dummy's knees and upper legs, and on the structure in front. If this is a first row seat, which is occupied, then considerably higher loads will act on the seat than in a single seat dynamic test.
  3. Influence of the arm movement. The structure in front can influence the arm movement and impact between the arm and the head takes place. In the case of the arms it is unlikely that this will happen in the same way in every test. So provisions should be taken to prevent such a situation. In that respect such a situation does not need to be simulated in a component test.
- The test pulse and/or the contact between other parts of the dummy and the impacted structure in front can result in structural deformations and movement of this structure, which changes the dynamic response

at the moment of impact. Consequently in such a case the head decelerations can change and a different HIC value will be obtained than if the head impacts the structure only. Whether this has a large influence on the HIC value or not depends on parameters such as the time and severity of the pre-impact by the other dummy part, the overall and the local stiffness of the impacted structure, and the weight of the impacted structure.

- In order to simulate an impact situation properly by means of component testing, the test device must be able to represent the dynamic behaviour of a full size dummy in a full scale test (see also the next section). Depending on the type of test device, the dummy head degrees of freedom, the dummy head to torso connection and stiffness or the upper torso weight are not properly represented. Whether or not this has a significant influence on the test results is very much dependent on the specific impact situation that is tested. In the case of complex impact situation, a full-scale test will always be necessary to verify the component test results.

Problems with component HIC test result correlation

When trying to prove that a component HIC test properly simulates the full-scale HIC test, the question arises which parameters have to be compared. The HIC value is certainly the main parameter in judging if a certain impact situation causes head injury to the occupant. However, two completely different impact situations, resulting in completely different head acceleration time histories, may still have the same HIC value. So the HIC value alone is not sufficient to show correlation.

If the component test would be an exact simulation of the full-scale test, the measured resultant head acceleration time histories would be the same. Consequently not only the HIC value, but also the length and the times T_1 and T_2 of the HIC interval would be the same. So for a proper correlation the head acceleration time history, the times T_1 and T_2 and the HIC value must be the 'same'. Since differences can not be prevented the results for the component test should be conservative. Besides these parameters which can be measured objectively, the dummy head movements and the structural dynamic behaviour and failure mode(s) of the impacted structure must also be the same in the component test and in the full-scale test.

Even if a component test device shows good correlation with full-scale test results for a particular impact situation, the question remains whether or not this will also be the case for other impact situations. Based on the previous considerations, a component test must fulfil two conditions if it has to replace a full-scale test:

1. The dynamic behaviour of the used impactor device itself must properly represent the dynamic behaviour of the dummy.
2. The impact situation must be realistically simulated (i.e. head path at and after impact, the head velocity at impact, dynamic behaviour of impact structure, failure modes of impacted structure, etc. must be the same as in the full scale test).

The first condition is given by the test device and is either fulfilled or not. However, if this condition is fulfilled for one impact situation, it does not necessarily mean that it is also fulfilled for other impact situations (see previous section). The second condition can be very hard to fulfil, or even impossible without doing a full-scale test. In the latter case component testing becomes unnecessary if no further development is required (e.g. due to HIC < 1000). Even if component testing can be used for development work the impact situation can change due to seat or interior modifications, and the component test is not valid anymore.

Although work has been done by the Society of Automotive Engineers (SAE) (SEAT committee) in co-operation with MGA Research Corporation to come to a simplified certification procedure using component testing only, no results have been published to date indicating that satisfactory results have been obtained. In this study a comparison between the results of full scale testing and an analytical model (MADYMO) has been made. However, the data was not consistent enough, nor sufficient to derive any conclusion with respect to the use of such analytical models for certification purposes.

In spite of the problems to show correlation between the component and full-scale test results, there are some situations in which, according to the author, component testing is sufficient to show compliance with the HIC requirements. Impacts situations such as glancing blows on relatively flexible structures (sidewall panels, glare shield, etc.) or impact on structures with a low and single failure strength (small bulkheads) often result in (very) low HIC values. Comparing such impacts with the results of full scale HIC tests on much stiffer structures can often be sufficient to prove that also in reality the HIC value for these impacts will be well below 1000. An expensive full-scale test of the particular impact situation is then unnecessary.

Dynamic seat testing and certification in the future

The experience has taught PILATUS that most of the PC-12 customers want an interior that fits his/her specific needs. Consequently, flexibility with respect to the number of seats, the interior lay-out and the type and location of interior items such as cabinets and the lavatory are very important to make the product attractive to the customer. This flexibility must be anticipated during the design phase of the seats, interior and the aircraft in order to minimise the development costs during initial certification, but also later on when additional interior lay-outs and options are developed.

This section focuses on requirements that have to be fulfilled by the seat design to obtain such a level of flexibility at acceptable costs and, at the same time, still to fulfil the requirements of FAR 23.562. In the past one of the arguments against the dynamic seat and HIC requirements has been that interior customisation is only possible at extremely high costs. However, this is not necessarily true. Also a test program and certification procedure is proposed in which component and full-scale HIC testing are combined. This testing can be done in such a way that HIC critical areas can be recognised early in the seat certification program and, together with a proper seat design, the number of (failed) full-scale tests is reduced to a minimum.

Possible design solutions for impacts on bulkheads and cabinet walls will only be discussed shortly.

Seat design for HIC

In order to avoid HIC problems and to improve the cabin flexibility it is clear that the head X-displacement should be as small as possible. If, due to the short seat pitch, impact still occurs on the back of a seat or on another interior item, the impact velocity should be as low as possible. There are three parameters that are mainly responsible for the amount of head X-displacement and the magnitude of the head velocity:

- Seat flexibility.
- Restraint system locking characteristics and installation.
- Dummy deformations.

The first two of these parameters can be influenced considerably by the seat designer, whereas his/her influence is limited in the case of the dummy deformations.

Although decreasing the seat flexibility has a positive influence on the head trajectory and velocity, it will, in general, increase the loads on the seat and seat occupant (this is further discussed in the section about the dummy deformations). In general a stiffer seat means also a heavier seat.

The aim of a properly functioning restraint system is to reduce the amount of belt that is released before inertia reel locking. This has a favourable influence on the head trajectory and velocity, but also on the seat and occupant loads because it reduces the velocity difference between the seat and the occupant. A good functioning restraint system can be obtained by setting the lock up g-level as low as possible (normally 1.5 g for passenger comfort) and to provide a direct and low friction routing for the shoulder belt. The latter will transfer upper body movement directly into inertia reel rotation, resulting in a minimum amount of belt release.

Dummy deformations of the pelvis and chest area due to lap and shoulder belt forces causes the dummy to slide forward on the seat cushion. These dummy deformations result in a velocity difference between the dummy and the seat. Once the softer parts of the dummy have been completely compressed this velocity difference is equalised in a very short time. The resulting dynamic loads cause accelerations of (parts of) the dummy that are well in excess of the maximum pulse acceleration of 21g. Reducing this velocity difference between seat and occupant will reduce these dynamic effects and thereby reduce the maximum loads on the seat and the occupant. One way of achieving this is by the installation of belt tensioners.

Even with a very stiff seat and a good functioning restraint system, it will be difficult to avoid impact if the seats have a small seat pitch (31" - 32"), especially for 95th percentile occupants. In such a case the head velocity at impact should be as low as possible. Fig 7 shows the head trajectory and corresponding resultant head velocity for respectively a stiff and a flexible seat.

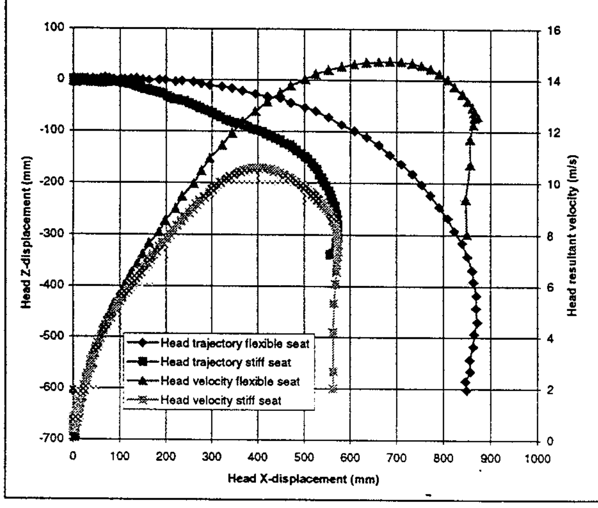

Fig. 7 Head trajectory and resultant head velocity for a flexible and a stiff seat.

Although these two seats have large differences with respect to the absolute value of the head displacement and velocity, the shape of the curves are more or less the same. This means that for most seats the impacts will occur with a head velocity, which is at least between 80% to 100% of the maximum head velocity. Impacts at about X = 300 – 400 mm are not possible because the seat pitch or the distance between the seat and bulkhead is then too small for the seat occupant. At the end of the curve, when the head starts to rotate forward and moves downwards more than forward, the head velocity drops very quickly with increasing X-displacement. Consequently, an inch more seat pitch or an inch more distance to a bulkhead can mean the difference between a HIC value over 1000 or a harmless glancing blow. This is especially true in the case of impact near the top edge of a seat backrest. So it can be concluded that the maximum head velocity must be as low as possible, because in the design phase of the aircraft, when the exact seat pitch is not yet known, impact at the maximum head velocity must be expected.

If impact takes place, the impacted structure must deform sufficiently such that the accelerations in the dummy head are low enough to obtain a HIC value below 1000. Furthermore the impacted structure must absorb the impact energy by means of permanent deformation. If it is absorbed by elastic deformation of the structure, the energy is stored as spring energy in the structure and will be given to the dummy head. Consequently the rebound velocity of the dummy head is high. This will then result in a higher HIC value than if the energy is absorbed by permanent deformation. This can be explained as follows.

In an ideal case all the impact energy from the dummy is absorbed by permanent deformation of the impacted structure. Then the rebound velocity is zero and the total velocity change of the dummy head equals the impact velocity (in reality this is not possible because elastic deformation has to occur before permanent deformation takes place). On the other hand if all impact energy is absorbed by elastic deformation and no energy is absorbed by permanent deformation and internal friction, the rebound velocity would be equal to the impact velocity and the total velocity change would be twice the impact velocity.

The HIC formula is an integration of the area under the head acceleration-time curve. The total area under this curve is equal to the velocity change of the dummy head. In the case of the elastic rebound the area under the curve will be twice as large as in the case where all impact energy is absorbed by permanent deformation. If the two impacted structure cause the same peak acceleration level, the acceleration-time curve for the elastic rebound impact must be much wider than the curve for the no-rebound impact. Consequently also the HIC value will be higher for the elastic rebound impact. So it can be concluded that the rebound velocity should be as low as possible.

When impact occurs on the seat backrest in front, the overall stiffness of the seatback structure will be too high (required for a good head trajectory in the case of a seat with shoulder belt) to get a HIC value below 1000. This means that local stiffness, at the location of impact, need to be reduced to allow sufficient local (permanent) deformation to provide an acceptable deceleration level. Local padding can provide this. The following example gives an idea of the required amount of padding in the case of such an impact.

The HIC value is defined by:

$$HIC = \left\{ (t_2 - t_1) \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) \right]^{2.5} \right\}_{max.} \leq 1000$$

Where
t1 = initial integration time
t2 = final integration time
a(t) = total head acceleration in units of gravity

Assuming an impact velocity of 12 m/s and a constant deceleration a_0 of the head during the impact, this deceleration and the required deformation distance can be easily calculated. The time interval to stop the head is:

$$t_2 - t_1 = \frac{v_0}{9.81 a_0}$$

The HIC formula can be simplified to:

$$HIC = (t_2 - t_1) \cdot a_0^{2.5} = \frac{v_0}{9.81} \cdot a_0^{2.5}$$

and: $$a_0 = \left[\frac{9.81 \cdot HIC}{v_0} \right]^{\frac{2}{3}}$$

With HIC = 1000 and v_0 = 12 m/s $\Rightarrow$ a_0 = 87.42 g

The required stopping distance is then:

$$s = \frac{v^2}{2 \cdot a_0 \cdot 9.81} = 0.084 m$$

In the case of a stiff backrest most of this stopping distance has to be provided by deformation of the local padding material, which means that about 3 inches of padding are required. However, investigations (2) have shown that a high deceleration at the beginning of the impact results in a shorter stopping distance at equal HIC value. So padding materials should be selected for such force-deformation characteristics.

The investigation (2) also presents data that the HIC value can change considerably even for minor changes in the point of impact. In general this is caused by local changes in the structural layout and stiffness of the impacted structure near the point of impact (in (2) the installed monitor causes the large variation of the HIC value). Therefore the structural layout of the area of potential impact should be as regular as possible. Special attention has to be given to shoulder belt guides, backrest shrouds, magazine pockets, tray tables, armrests, entertainment system, etc. Variation in HIC value as a function of the impact location can be investigated by component testing. If the dynamic behaviour of the impacted structure and the dummy and the possible interaction between other dummy parts (e.g. legs) and the impacted structure are (about) the same for the whole impact area one full scale test can cover the whole impact area.

Padding of bulkheads, interior cabinets and panels is often

not acceptable because of aesthetical reasons. Special solutions such as presented in (2) or as applied to the PC-12 lavatory cabinet can be used. Basically these solutions consist of weakening of the impact area to allow adequate deformation or failure of the structure. In the case of structural failure, possible occupant injury due to sharp edges, etc., needs to be considered.
Sidewall panels do not cause HIC problems in general because the impact is mostly a glancing blow. Only in the case of impact near a window cut-out, on sidewall panel armrest and on or near special features which are mounted to the sidewall (e.g. sidewall-integrated table, telephones, speakers, monitors, ashtrays, oxygen mask pockets, etc.) HIC problems can occur. Therefore these items should be located outside the potential impact areas whenever possible.

<u>Dynamic seat and HIC testing and certification in the future</u>

In order to comply successfully with FAR 23.562 with a minimum amount of testing and seat and interior modifications throughout the certification process, the seat specification must contain requirements with respect to head X-displacement, head velocity and seat to seat impact. Although the exact number of cabin layouts may still be unknown at the moment this specification is written, minimum comfort requirements can be used to define the above parameters.

A weight requirement will still be present in the specification, but it should be less important than the requirements for HIC. Compared to the old 9 g seats, a weight increase of the seat has to be expected. However, as soon as the seat manufacturers have developed more dynamic seats, the weight of dynamic seats will decrease due to the use of more efficient structures and materials.

Besides a proper seat specification, also a good test program can help to reduce the total costs of the development and certification program. In order to offer as much flexibility with respect to the cabin layout as possible, a large number a layout variations (number of seats, seat location, different type, amount and location of cabinets) should be considered. Starting off with these cabin layouts a test and certification program can be started which could be as follows:

- Determine the seat head displacement and head velocity curves. If the seat has not yet been tested, which will normally be the case early in the program, assumptions have to be made for the head X-displacement and velocity. This can be difficult if the seat structure is a completely new design.
- Determine the different cabin layouts, which are possible within the available cabin space. Now the marketing department has to decide which interior layouts must be certified, and which are 'nice to have'.
- Determine all possible impact areas for all cabin layouts and for different seat occupant sizes (5^{th} female till 95^{th} male).
- Make an overview of the type of impacts, impact velocity range and the impacted surfaces. The requirements with respect to the maximum head trajectory and head velocity can be based on the impact situations. For example, if impact can not be prevented because the seat pitch is too small, requirements for the head velocity can be defined in order to obtain a HIC value below 1000 without too much padding material. Component testing to evaluate different energy absorbing material and padding shapes should support the definition of the requirements. This impact evaluation can be done by the aircraft manufacturer or be subcontracted to the seat manufacturer.
- The results of these component tests can be used in the final seat design. After successful development testing the design can be frozen, and the certification testing can be performed. The head movement is digitised to obtain the head trajectory and velocity curves.
- The head trajectory analysis for the defined cabin layouts, whether offered to the customers or not, is repeated with the head data from the certification tests.
- All impact situations are determined and a worst case selection is made based on velocity, impact angle, impacted structure and the result of the component tests earlier in the program.
- Component testing can now be used for those impact situations that need to be verified, but will never result in a high HIC, e.g. impact on regularly shaped sidewall panels, certain impacts on small bulkheads, glancing blows on flat surfaces (bulkheads, seat backs). Component testing should also be done at this stage to get information on how the HIC value changes as a function of the impact location. This will support the choice of the impact situation(s) for full scale testing and thereby minimise the amount of tests.
- Critical and complicated impact situations should be tested by full scale testing in order to properly simulate phenomena like dummy legs to seat interaction, changes in the dynamic behaviour of the impacted structure due to this interaction, deviations from the theoretical impact location due to the absence of floor deformations, etc.

<u>Conclusions</u>

Based on the experiences gained during the certification of the PC-12 crew and passenger seats, PILATUS Aircraft Ltd. has reached the conclusion that, although component HIC testing is a very useful tool for seat and interior development and for determining critical impact situations for full scale testing, it can not replace full scale testing at the moment or in the near future. Each of the available component test devices has its own particular shortcomings and therefore its own particular type of impact for which it is most suited.

Seat dynamic and HIC testing will be less of a 'trial and error' process, and therefore be less costly, if these requirements are accounted for in an early stage of the seat and interior design and a test program is chosen which identifies the problem areas early in the certification program. A weight penalty should be accepted if this results in a short head X-displacement and a low head maximum velocity. At the same time however, the seat manufacturers should develop more efficient seat structures, which offer such short head X-displacement and low head velocity at the lowest weight possible.

References

(1) Federal Aviation Regulations, Part 23 Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes; Amendment 36; §23.562, May 1988.

(2) Robert Käser et al: "Development of a head impact compatible partition wall", Proceedings of ICAS Conference, Anaheim (USA), 1994.

(3) Policy Letter TAD-96-002, "Simplified Procedure for Addressing the Head Injury Criteria of §25.562", Manager, Transport Airplane Directorate, Aircraft Certification Service, ANM-100, Federal Aviation Administration.