MODELING OF AIRCREW HEAD AND NECK LOADS EXPERIENCED DURING EJECTION

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Compagny and research laboratories overview

Société d’Exploitation des Matériels Martin-Baker (SEM MB) was established in 1959 in joint ownership with SNECMA. It has 37 employees and has manufactured over 6000 Martin-Baker ejection seats for French produced aircraft. More than 600 aircrew lives were saved, so far. SEM MB offer a comprehensive range of product support hardware and services in France and abroad.

Institut de Médecine Aérospatiale du Service de Santé des Armées (IMASSA) is the institute of aeronautical medicine of French Army. The IMASSA’s ancestor was created in 1945 with the Centre d’Etudes de Biologie Aéronautique (CEBA). The aerospace medicine of defense consists in five fields of skills with medicine in operational units, hospital medicine, expertise medicine, training and research. Areas of research are cognitive sciences, aeronautical physiology and performance, sensorial physiology and flying safety.

ENSAM BioMechanics Laboratory (LBM) was created in 1988 and was labeled by the Centre National de la Recherche Scientifique(CNRS) in 1997. The LBM research fields are oriented towards the analysis of musculo-squelettal systems, in vivo explorations, experimental analysis and numerical simulations, particularly in spine. The spine biomechanics is a one of expertise part of the LBM.

Introduction

The advent of Helmet Mounted Devices (HMDs) has seen the issue of increased head and neck injury risk become of prime importance. Therefore, SEM MB, IMASSA and LBM will jointly conduct an investigation regarding this risk of injury of two in-service seats, the Mk10 seat fitted on the Mirage 2000 and the Mk16 seat fitted on the Rafale. The objective of the co-operation between IMASSA, LBM, SEM MB and Martin-Baker is to combine simulation tools.

The whole investigation will be divided into two main parts:

In the first part, we will:

- Define the Technical requirements
    - crew mass and size range,
    - to include both a male and female aircrew ?
    - aircraft and seat types
    - escape flight envelope
    - Helmet design
- Perform the ejection simulation and inject the findings into the physiological model

The second part will consist in:

- running the physiological model and conducting analysis of the results.
- proposing remedial solutions should the results indicate a high risk of injury

Background

Since the first lethal mishap in aviation because of skull injury, Wells [WEL15] recommends wearing a protective helmet against shock.

Helmets receive visual systems to increase pilot efficiency during missions. This kind of equipment meets modern jets technological requirements. These systems increase the pilot's operational capabilities but induce biomechanical consequences for the neck. Anton [ANT90] shows that helmet mounted devices (HMD) increase neck injury risk for both acute (during ejection) and chronic injuries.

Devices as night vision goggles (NVG) increase the overall head mass and also shift forward the center of gravity of the equipped head, so inertial properties of the equipped head are modified [HEN90]. The consequences are increased stresses sustained by the cervical spine, exacerbated during dynamical environment such as ejection. The result is an increased neck injury risk during ejection, when crewmembers are equipped with NVG or HMD [PLA03].

For the moment, the neck injury rate is quite low with about 1% of injuries [PER03], because all missions do not require HMD and because female crewmembers are quite rare.

In car crashes females would have a greater neck injury risk from 1.4 to 3.4 compared with males [LOR96] [MOR88] [DAU00] [DOL69]. Also, according to Freeman [FRE98], lighter and smaller subjects have greater injury risks than regular stature people. During car crashes, women are twice as often wounded at the neck than males [BER99].

Presentation of the aircraft and seats

Mk 10 seat

The Mk10 seat is installed in the Mirage 2000 used in the French Air Force. It is a 1970’s technology design fitted with a GQ1000 parachute, a ‘g’ switch and a barostatic controller. It is a rocket motor seat that gives a zero/zero capability. The mass of the Mk10 seat is approximately 90 Kg (~198 lb). The acceleration during the gun phase is between 14 and 16 g (50%ile male aircrew). The seat was qualified for an ejection up to 625 KEAS.

Figure 1 : MK 10 Seat

Figure 2: Mirage 2000

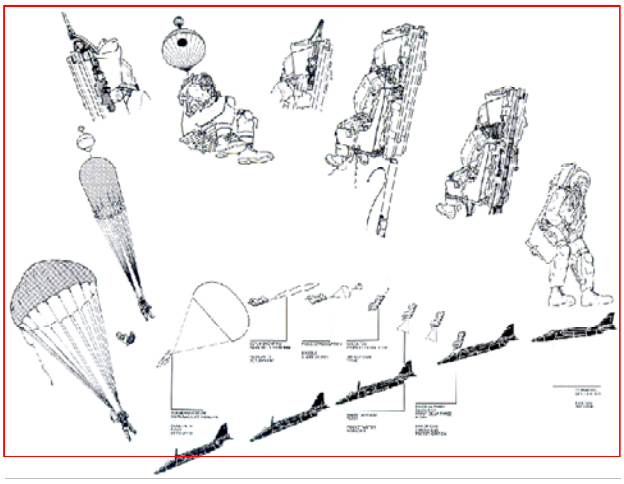

Figure 3 : Different phases of Mk10 ejection

Mk 16 seat

The Mk16 seat is installed in the Rafale currently used by the French Navy and the French Air Force. It is a 1990’s technology design fitted with a GQ5000 parachute, the latest technology of mechanical parachute controller (pitot tubes, ‘g’ switch and barostatic controller), a new technology of gun cartridges. It is a rocket motor seat that gives a zero/zero capability.

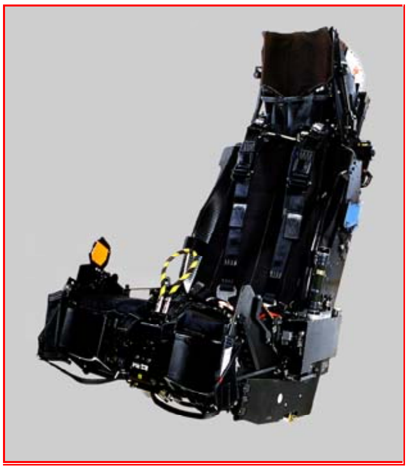

Figure 4 : Mk 16 Seat

Figure 5 : Rafale

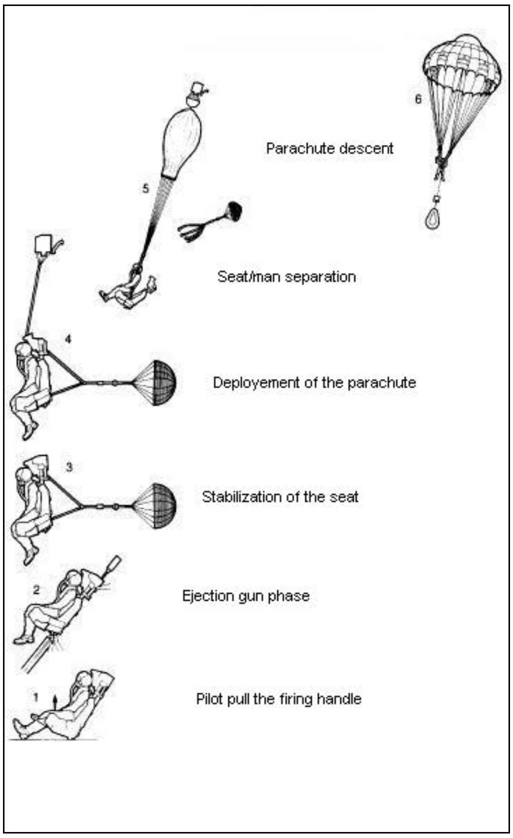

Figure 6: Different phases of Mk16 ejection

Figure 7 : Mk16 seat

Differences between the Mk10 and the Mk16 seats

The Mk10 seat is a 1970's technology design when the Mk16 seat is a 1990's technology design. That means that the latest improvements are currently used in the Rafale seat. Therefore, there are some major differences between these two seats :

The following items are different:

- Stabilization of the seat
- Cartridges technology
- Deployment of the canopy

It is important to say that the risk of injury doesn't come from the seat design but from the added mass on the head of the aircrew. And the objective of the study is to adapt the seat to this increase in mass. With existing helmet systems and seats, reports of serious neck injury are very few.

Stabilization of the seat

The Mk10 seat is stabilized on one single point (scissor shackle fitted at the top of the headbox) when the Mk16 seat is stabilized on four points.

That is why the Mk16 seat is always stabilized 'into wind' when the Mk10 seat can roll and so the head could be in a lateral direction, which is considered the most injurious direction for the neck.

Cartridges technology

The Mk 16 seat used the latest technology of cartridge, the 'choked cartridge', but the Mk10 seat used a standard cartridge technology (with nitro-cellulose). Areas of the choked cartridge, the seat performance is enhanced. There is less variability in the ejection gun performance and we can accommodate a wider aircrew mass range to meet both the DRI criteria and achieve the required ejection gun velocity.

Deployment of the canopy

There is an important difference between the Mk 10 and Mk 16 seats regarding the deployment of the parachute canopy. This difference is due to the design of the headbox.

For the Mk 10 seat, the canopy is deployed before the rigging lines when for the Mk 16 the rigging are deployed first.

The purpose of this improvement is to have a soft inflation and so to reduce the acceleration applied on the neck of the pilot.

Presentation of the numerical simulations tools

The Ejection Seat Model© used by SEM-MB

The Martin-Baker Ejection Seat Model, SEAT6D, simulates the entire ejection sequence, from the initial aircraft dynamics, through the catapult, emergence, rocket, drogue, seat-crew separation and recovery parachute phases. The motion of every body is calculated in six degrees of freedom (6-DoF or three dimensional linear and rotational motion). The operation of every relevant device is modelled, including the signal system delays, the catapult, the rocket burn, the sequencing devices (mechanical and electronic), mortar reactions, the parachute deployment and inflation and drogue bridle operation. The seat and parachute aerodynamics are modelled including the effects of cockpit emergence, rocket plume interaction, and seat wake interaction with the drogue.

It has been configured and validated for most Martin-Baker seat types including the MkF16F (Rafale), MkF10M/Q (Mirage2000).

This validation involved matching to seat test data from zero/zero tests up to 625 KEAS. The matching includes the trajectory, angular rates, accelerations and, of course, head and neck loads.

The outputs from the model include numerical output of :

- trajectories and other dynamics of all bodies (relative to ground and/or to each other);
- forces and moments;
- physiological metrics, e.g. acceleration and dynamic response radicals, MDRC;
- discrete event reports (e.g. rocket ignition, mortar firing, sequencer mode selection);

The motion of the simulated bodies can also be viewed in 3-D. This feature aids model validation (by comparison to film or video data) and also shows aircraft fin clearance and seat stability more clearly than graphs. It is also a useful tool for illustrating ejection seat function.

LBM head neck model

A numerical finite element model of a head and human neck has been developed by the Laboratoire de Biomécanique (LBM) of ENSAM, in collaboration with the Laboratoire d’Accidentologie et de Biomécanique (LAB) [BER99] [FRE03].

In order to quantify neck injury risk during ejection with an equipped head, an explicit finite elements code “Radioss” was used and numerical simulations were realized with a human neck model. The results of simulations are moments in Y- axis and efforts in Z - axis along the cervical spine. These values are injury parameters because flexion extension, traction, compression are injury mechanisms which are responsible on fractures, sprain, ligaments elongations or neck pain [LEC02].

The model was built on the neck of 50th percentile man geometry. The head’s model consists of a 50th percentile Hybrid III manikin head. The morphometry of the cervical vertebrae and the intra vertebral discs was adapted from Maurel [MAU93] and Panjabi [PAN93]. Anatomical structures were represented such as vertebrae, ligaments, capsules of joints, muscles, and soft tissues of the throat. Head and vertebrae were modeled by rigid bodies, soft tissues and muscles geometry were included in the model and adapted from Visible Human Project [MED97]. These different soft tissues were represented by volumes elements. All the different constitutive parts of the model were modeled by using various kinds of finite elements and material properties to represent adequate mechanical behavior of each component [BER99].

The LBM model was validated against available experimental data with voluntary human subjects and human cadavers. The model was validated in static for functional motion units with experiments of Wen [WEN93] and Watier [WAT97]. The model was validated for frontal, lateral and oblique shock with experiments of the NBDL by Ewing [EWI76] et Wisman [WIS87] For the rear impact, the LBM model was validated with experiments of Prasad [PRA97], Kallieris [KAL91] and by Bertholon [BER99]. In order to validate the injurious mechanisms of the LBM model, torsion and compression were validated with test results of Myers [MYE91] and Nightingale [NIG91-97].

Methods

- Experiments

Experimentations consisted in a 0/0 shot with a MK10 ejection seat and an instrumented manikin. The 0/0 shot was performed by Centre d'Essais en vol (CEV) of Cazaux, France.

The manikin was a 95th Hybrid III. The manikin was instrumented with accelerometers in the chest area in order to quantify accelerations, and with gyro-meter to asses dummy roll, pitch and yaw rates. The manikin was dressed in flight clothing, wore a Gueneau 458 helmet, with bayonet to receive Ulmer oxygen mask. Accelerations data stored during the 0/0 shot were the boundary conditions for simulations.

- Numerical simulations

After data treatment, boundary conditions in terms of displacements were input at T1 vertebrae. The 50th percentile human head and neck model was positioned in the seated reference position of a MK10 seat. The contact between head (respectively helmet) and headrest was taken into account.

Results

- Experiments

The manikin accelerations in X and Z - axes were stored during the gun phase of a 0/0 shot performed by CEV of Cazaux (France).

- LBM numerical simulations

Simulations were performed in four cases : head bare and three various helmets which are shown below, their inertial properties are adopted from literature [ASH97]. In the following simulations, accelerations of the chest in x and z - axes were input in the model. Preliminary results are presented hereafter :

Figure 8 : Case n°1 [WEB 1], case n°2 [WEB 2], case n°3 [WEB 3].

Figure n°9 represents the maximal of flexion/extension moments along the cervical spine during gun phase. X - axis describes values of maximal flexion or extension. The moments of flexion are positive and are on the right of the graph. The moments of extension are negative and are on the left of the graph. Y- axis represents the cervical spinal level.

Figure n°10 represents maximal compressive forces along the cervical spine during gun phase. X - axis describes values of maximal compression on the neck. All of the maximal forces are negative, there are compression efforts on the cervical spine. Y- axis represents the cervical spinal level.

On these two graphs, purple represents the bare head, pink represents the case n°1, the light blue represents the case n°2, and the dark blue represents the case n°3.

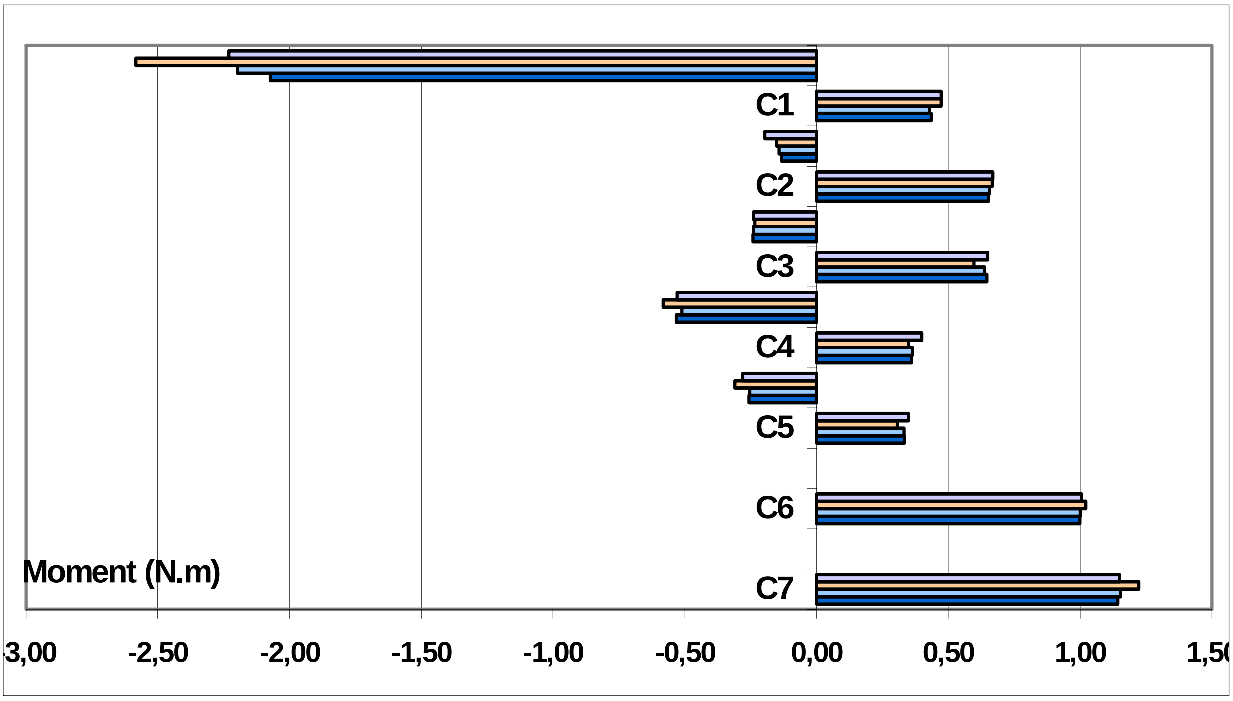

Figure n°9 : Maximal moments along the cervical spine.

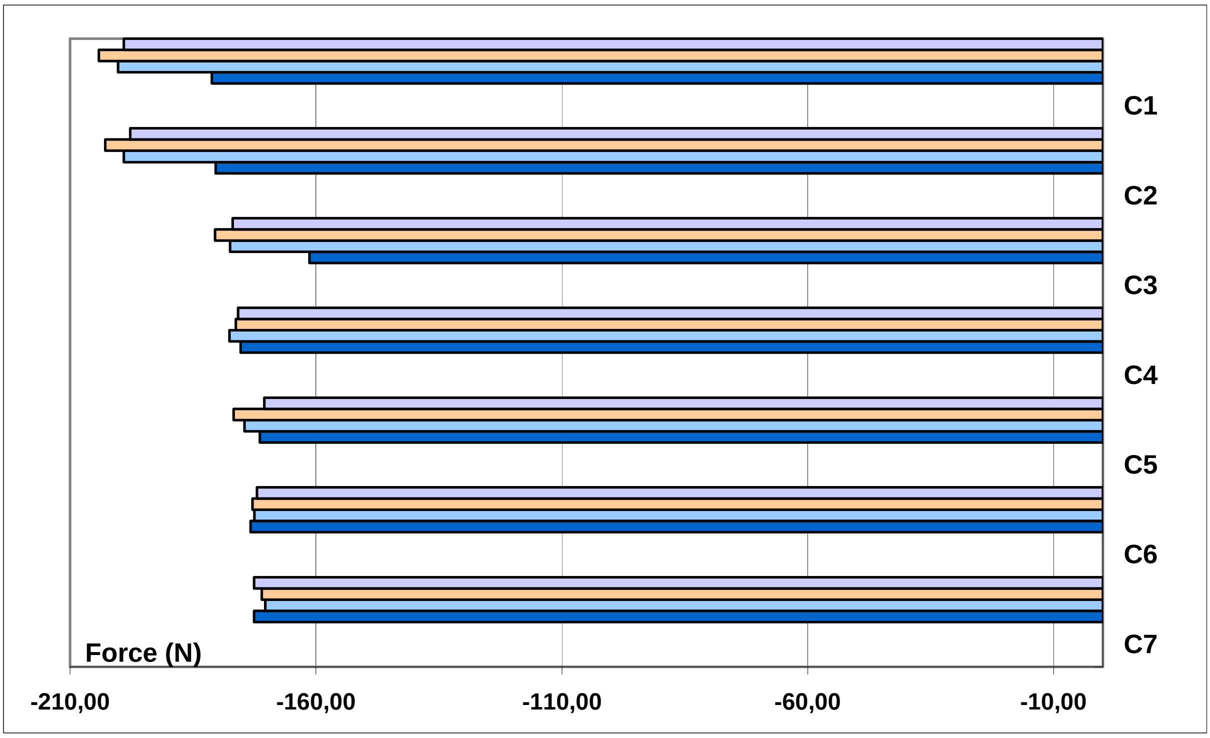

Figure n°10 : Compression efforts along the cervical spine.

Maximal moments appear at C0/C1 in extension (-2.58NM) and at C7/T1 level in flexion (1.22NM) with the worst equipment.

Compressive maximal values appear at C0/C1 (208N) and at C1/C2 level (173N), with the worst helmet.

All of the maximal values are under injury level for flexion/extension and for compression.

Conclusion

SEM MB : Assessment of predictions and test results

The results of the ejection simulations and tests will be analysed to determine the acceptability of the aircrew head and neck loads during ejection while wearing the new helmet.

Should the results indicate an unacceptably high risk of head / neck injury, then a further programme of working that investigates and develops remedial modifications to the helmet, seat or aircrew flight clothing assembly would need to be considered.

Remedial modifications

Lowering the head / neck loads and moments during ejection can potentially be achieved through modifications to the helmet, the seat or the flight clothing assembly.

Helmet modification.

Aerodynamic forces and moments acting on the helmet can be modified by changing its shape and / or size. Inertial forces and moments on the head induced by the helmet can be changed by lowering the mass of the helmet and / or redistribution of the mass to optimise the centre-of mass position. Jettisoning parts of the helmet (e.g. camera pods) at the moment of ejection initiation is a possible method of changing both the aerodynamic and inertial characteristics of the helmet.

Seat modification.

There is a range of seat design changes that could be considered. Firstly, it may be possible to change the aerodynamic characteristics of the seat in the area of the headrest, to modify the airflow over the top of the helmet. Another approach involves improving the seat stability, based on the principle that a seat that is well stabilised 'into wind' will reduce forces applied to the head in the lateral direction, which is considered the most injurious direction for the neck. Other modification strategies are possible.

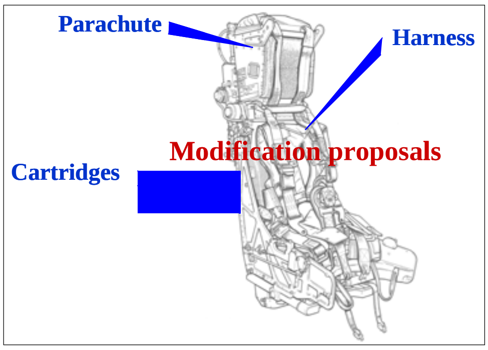

Figure 11: Mk 10 modifications

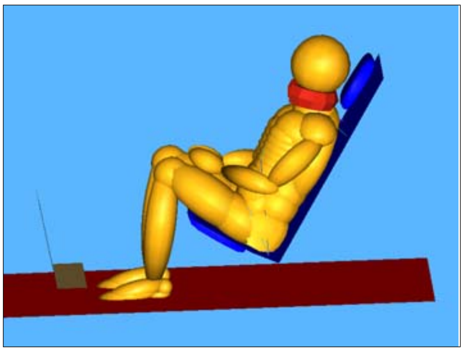

Figure 12 : Inflatable collar device

Aircrew clothing assembly.

Finally, it may be feasible to add features or devices on the flight clothing to provide additional support to the head, this protecting against gross head / neck motion.

LBM / IMASSA

Once the numerical simulation validated, it should allow research of optimal distribution of helmet mass around the head gravity centre, in order to minimize the risk of cervical injuries in case of egress emergency.

In the future

- *Coupled approach*

As explained in the preceding section, the neck injuries can occur at various point during the ejection sequence (from the gun phase to the inflation of the canopy) and across a speed range.

To have neck load predictions, we will have to combined ejection seat model (SEAT6D$^{©}$) and the neck model (LBM model). In the first step, we will not include aerodynamic effects into the model (simulations performed only for speed lower than 250 Kts).

Moments and tensile/compressive forces along cervical spine will be quantified and compared to injuy baseline values in order to determinate if the ejection is safe or not for the crewmembers neck.

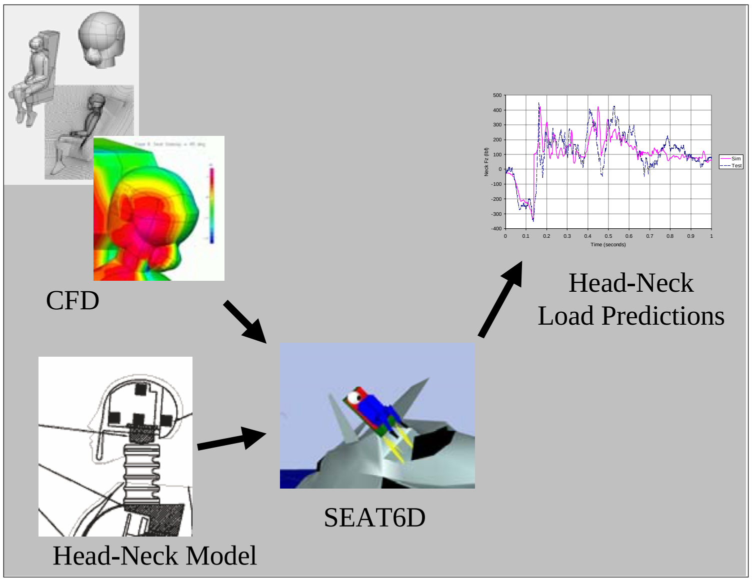

Figure 18: Coupled approach

- ***Windblast***

Computational Fluid Dynamics

The next step of the study will consist in introducing aerodynamic effects for high speed ejection, and computational Fluid Dynamics (CFD) will be used to predict the aerodynamic properties of the whole seat and also specifically of the head and helmet.

CFD is used to build up a database of aerodynamic coefficients (lift, drag, side-force, pitch, roll and yaw moments) against parameters such as seat incidence, Mach number, and head orientation. This database is used to generate the aerodynamic loads in the SEAT6D model.

The changes in aerodynamic properties arising from new HMD designs can be predicted using the CFD; and the consequent effect on head and neck loads predicted using SEAT6D.

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Electronic resources

[WEB 1], www.rotorcraft-tech.com

[WEB 2], www.voodoo.cz.

[WEB 3], www.hec.afrl.af.mil