ESA STUDY – SAR MODELLING AND SIMULATION RESULTS

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THE SAR DEPLOYMENT MODELLING PROJECT

The “SAR Deployment Modelling Project” was established between the European Space Agency (ESA), Matra Marconi Space (MMS) and Fedem Technology AS in 1996. The project will be terminated in October 1999.

The purpose of the project was to develop a software tool capable of simulating the deployment and latching of space mechanisms.

ESA initiated this project because they claimed that no single simulation tool was able to predict all behavioural aspects associated with the deployment of space mechanisms including electrical, mechanical and structural components.

MMS which is one of Europe’s leading companies in engineering and production of complex satellites and space instruments provides the hardware used in the project. MMS is also responsible for all hardware testing used in the final software validation

Fedem Technology AS was selected as the vendor of the FEDEM software which was selected due to its basic multidisciplinary modelling and simulation capabilities

SOFTWARE BENCHMARKS

Five different advanced space mechanisms were selected as the main benchmark examples for the FEDEM software. The selected mechanisms were MIMR RDM, GOMOS, PDM, MHSA and ASAR.

The mechanisms were selected as benchmark examples based on the available hardware test results and their different characteristics with respect to modelling and simulation requirements as shown in the following table.

Mechanism	Depl. time	Inertia mass	System frequency	Initial depl. energy
GOMOS	< 1 sec	Low	High > 50 Hz	High strain energy and motor
PDM	> 2 sec	Very high	Low < 0.2 Hz	Low strain energy and motor
MIMR	< 1 min	Medium	Medium > 1 Hz	Motor driven
MHSA	1 min	Low	Medium 1 Hz	Motor driven

The objective of this paper is to describe how one of the benchmark examples GOMOS was modelled and simulated in the FEDEM software.

This paper describes the key design drivers, the mechanism architecture, and how simulation was used to identify and solve the problems that was found during testing of the first GOMOS prototype. It also provides a brief overview of the applied modelling and simulation methods.

THE GOMOS BENCHMARK

The GOMOS (Global Ozone Monitoring by Occultation of Stars) instrument is developed by Matra Marconi Space for the low Earth orbit ENVISAT-1 mission of the European Space Agency. The purpose of GOMOS is to provide a daily global geographical coverage of ozone vertical distribution by stellar occultation technique.

The GOMOS instrument embodies a UV-visible spectrometer fed by a fixed telescope. A Steering Front Mirror is used to successively orient the mirror line of sight towards pre-selected stars. The target star is acquired and tracked while it is setting behind the atmosphere. During occultation, the star spectrum becomes more and more attenuated by the absorption of ozone. Starting from these spectral data, a spectral differential processing method is applied on ground and the ozone vertical distribution accurately derived. The stars are acquired with a very high pointing accuracy (3 microrads). A picture of GOMOS is shown in Figure 1.

Figure 1 *The GOMOS mechanism*

A schematic overview of GOMOS is given in Figure 2 and a comprehensive description of the overall GOMOS architecture is given in [Humphries 97]

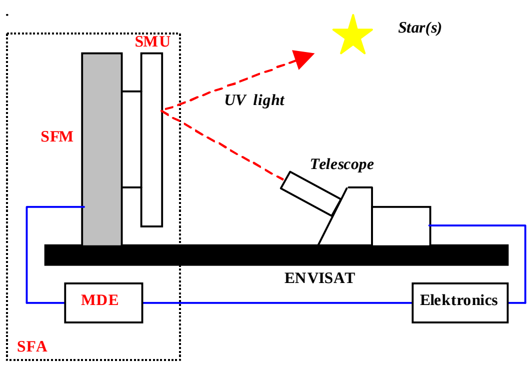

Figure 2 *The overall GOMOS architecture*

THE OFF-LOAD DEVICE

The GOMOS SFM hold down and release system is a multi-element system, and its distributed nature is the single most important factor for complicating the construction and appearance of the SFM. An assembly model of the main structural parts in this subsystem is shown in Figure 4.

The SFM subsystem which enables safe hold down and release comprises a redundant brushed DC motor driving through a reduction gear (1:112) that rotates a cam as shown in Figure 3.

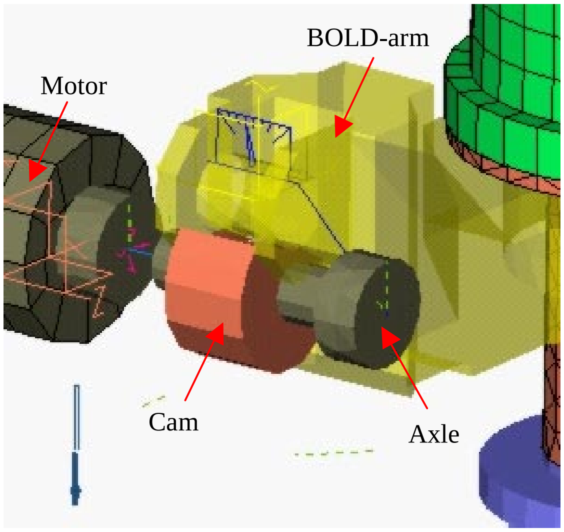

Figure 3 *The GOMOS SFM offload model*

The cam operates a Bearing Off-Load Device Arm (BOLD-arm), that is pivoted at the housing opposite the cam.

As the cam follower attached to the free end of the BOLD-arm is lifted, the BOLD-arm contacts the outer shafts at its centre, and moves the shafts axially in +Z direction.

After contact with the support towers additional cam lift deflects the BOLD-arm and the Turntable. This provides the required off-load force with spring compliance to compensate for vibration and thermal effects.

The Turntable is translated 1.2 [mm] in the +Z direction to engage and pre-load the off-load claws at three support towers. This elastic displacement is as mentioned above due to the rotation of the eccentric off-load cam.

The cam profile includes a small detent (over centre characteristics) at the fully locked position that will ensure that the cam will not rotate off during launch operation even if a considerably amount of strain energy is stored in the SFM.

The off-load operation is activated in orbit by driving the cam back from its equilibrium position using the DC motor. When the cam has passed the small detent the stored strain energy will drive the cam and the motor/gear-head assembly 310 degrees back to the initial position.

After the offload release the Turntable is free to rotate and GOMOS can start to track stars and perform ozone measurements.

OFF-LOAD PROBLEMS

One of many important functional requirements for the SFM is to support GOMOS during launch and under operation without imposing loads which can degrade the optical performance.

The SFM was therefore subjected to a full range of functional tests. These tests included stiffness, performance and microvibration response tests.

No major problems were encountered during the functional testing with the exception of the rapid release of the offload cam. The fully preloaded SFM has stored within it a considerably amount of strain energy. This energy is mainly stored in the elastic deflection of the Turntable and the BOLD-arm.

Upon operation of the off-load release motor, the cam rotated beyond its over-centre position, releasing the strain energy within the SFM.

The strain energy release caused a rapid acceleration of the off-load DC motor and the development of an extremely high shock impulse when the motor was hitting the end stops.

The torque generated was sufficient to shear the end stop and cause considerable damage to the motor gear head. The off-load actuator was replaced and a system of parallel resistors were introduced around the motor to increase the eddy current damping from the redundant motor.

The introduction of eddy current damping of the actuator motor considerably slowed the rate of the off-load release and completely eliminated the shock pulse at the end of the off-load release.

WHY SIMULATION

The damage caused by the off-load test release was an expensive and time consuming experience. However, the damage would have been much more critical if no tests had been performed and the accident had occurred in orbit.

Several questions had to be answered after the accident:

- Which parts had been damaged
- Why did the off-load release fail
- Could the failure have been predicted
- How can future problems be avoided

Experienced engineers at Matra Marconi Space were able to solve the problem by introducing eddy current damping. However, some of the questions were still not addressed

It was not possible to repeat the off-load test in order to measure the damping, peak loads, accelerations and energy distribution in the GOMOS SFM. The only way to solve the remaining questions was to establish a virtual prototype of the SFM and simulate the off-load test.

This was not a straight forward task because all electrical, control and mechanical components had to be included in the virtual SFM model in order to provide reliable simulation results. These requirements caused GOMOS SFM to be one of the selected benchmark examples in the “SAR Deployment Modelling Project”.

THE FEDEM MODELLING AND SIMULATION CAPABILITIES

FEDEM is a multidisciplinary simulation system based on a non-linear finite element formulation and control system modelling and simulation.

During the “SAR Deployment Modelling Project” major new enhancements have been developed and implemented in FEDEM to support all specified modelling and simulation requirements.

Some of the new FEDEM features/capabilities are:

- The mechanism links are represented by FE models (superelements) created in pre-processors like I-DEAS, PATRAN etc.
- The superelement mass and stiffness matrices can be reduced using static or component mode synthesis reduction (CMS)
- Each superelement is imported, positioned and used as a link in the FEDEM mechanism assembly
- A co-rotated frame is associated with each link (superelement) and the elastic displacements and stress results are calculated relative to this frame
- Large rotations and displacements of the links are included but the elastic displacements of each link is assumed to be small.
- The links are connected together with various joint types (revolute, ball, cam etc.)
- All joint types are based on master and slave techniques that are very numerical robust
- Lumped masses and inertias can be applied directly on the mechanism model
- Non-linear loads, dampers and springs can be attached between the mechanism links
- The control systems are created in a 2D environment and coupled together with the 3D mechanism model

- The solvers are based on various numerical methods like Newton-Raphson and Newmark integration schemes
- All structural and control system variables are solved simultaneously
- Simultaneous simulation and visualisation are supported
- The modes can be calculated and animated at specified mechanism configurations
- The stresses can be solved at specified mechanism configurations
- Direct interfaces to I-DEAS, NASTRAN, PATRAN and HYPERMESH.
- The mechanism motion can be animated with superimposed elastic deflections and stress distribution
- All modelling and simulation tasks are controlled by a uniform graphical user interface

With all these integrated capabilities FEDEM supports a multidisciplinary modelling and simulation environment that enables the users to create and test complex satellite systems.

THE GOMOS MODELLING PROCESS

The GOMOS SFM is a very complicated system with hundreds of mechanical and electrical components. However, to create a representative virtual prototype doesn't mean that all components have to be included.

In order to create a representative and computational efficient GOMOS SFM model simplifications had to be made. In order to reduce the model complexity and still maintain reliable simulation results a lot of knowledge had to be transferred from the design and test engineers to the analysts. This was a rather time consuming and error prone process due to both technical and organisational issues like:

- The analysts were not involved in the GOMOS design process and had to learn the mechanical system from scratch
- Engineers from the different disciplines were not co-located (ref. UK, Norway and Holland)
- Lack of compatibility between test and simulation results.
- Busy project leaders (ref. authors)
- Inconsistent terminology between engineers (and hopefully not language !)

The modelling and simulation of the GOMOS SFM involved test, draftsmen, structural and control system engineers from MMS and analysts from FEDEM AS. The most demanding task for the analysts was to understand the overall mechanical system and hence select what information they needed to complete the model.

THE GOMOS SFM MODEL

During the SFM modelling process a wide range of physical properties had to be estimated.

The structural stiffness and mass distribution of each link was represented by a finite element mesh. The mesh was optimised with respect to dynamic simulations and not detailed stress analysis

Some of the links in the GOMOS SFM were already modelled by MMS and validated in NASTRAN. These FE models were stored as separate bulk data files and referenced by the corresponding links in the FEDEM mechanism model file.

Other links were modelled by FEDEM AS in I-DEAS Master Series based on 2D drawings. These links were meshed and exported as native FEDEM files. These FE models were also referenced by the corresponding links in the same FEDEM mechanism model file. Figure 4 shows an assembly of the GOMOS SFM model.

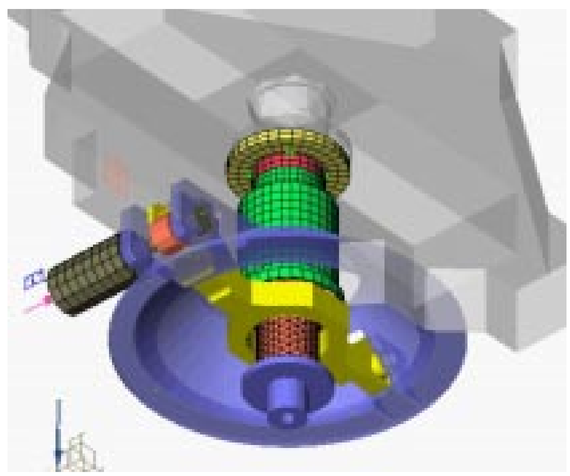

Figure 4 *The GOMOS SFM model*

Table 1 shows some key numbers for each link model.

Table 1 *MDE characteristics*

Link Name	Link ID	# DOFs before CMS	# DOFs after CMS
Support Housing	1	9870	66
CamAxel	2	672	12
Cam	3	726	96
OutputAxel	4	822	12
Gear	5	570	12
BOLD-arm	6	11256	36
Midshaft	7	4776	24
UpperIndMount	8	2538	12
Harnesshouse	9	8844	12
Flexpivot	10	2316	12
TableIntDisc	11	2892	30
Actuator	12	828	12
Turntable Assembly	13	3180	48
Total		42290	384

Figures 5 to 8 show some of the link models.

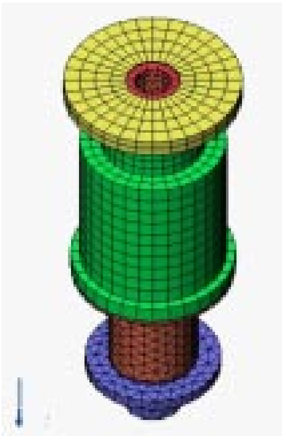

Figure 5 *The mid-shafts / interface disks etc*

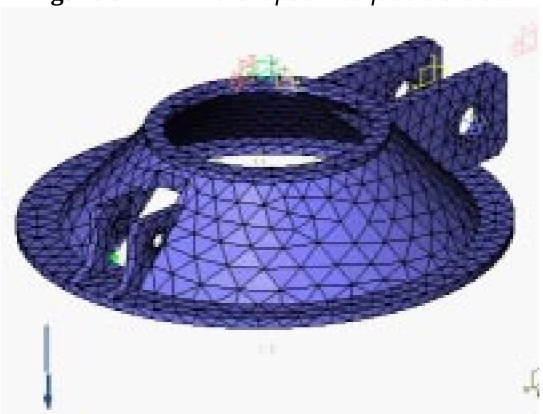

Figure 6 *The support housing*

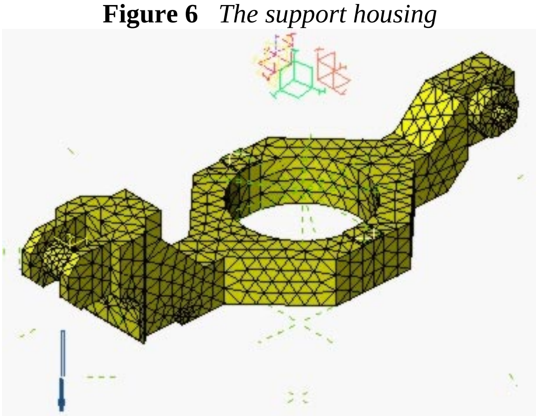

Figure 7 *The BOLD-arm*

All parts were positioned into the mechanism assembly and connected together with rigid, revolute, free and cam joints. The rigid joints were used to introduce a stiff connection between parts and ground with no relative movement. The revolute joints were used in the cam/axle system and in the BOLD-arm pivot points.

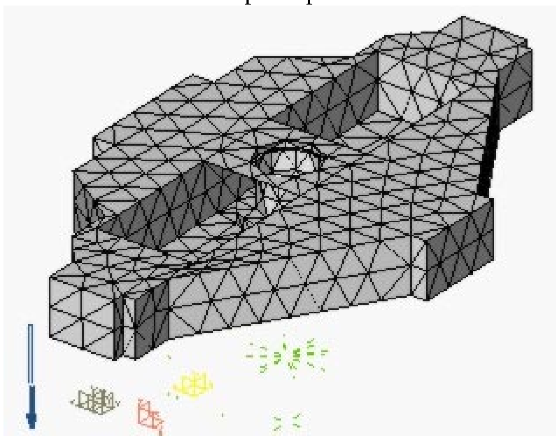

Figure 8 *The Turntable Assembly*

The free joints are generic joints with six degrees of freedom. The joint constraints are introduced by springs and dampers. Non-linear joints were introduced between the Turntable assembly and the shafts to allow a specified 1.2 [mm] free elevation in the +Z direction.

A pre-load of 200 N which is applied via a star diaphragm sub-assembly is implemented as a pre-stressed free joint.

Free Joints were also used to represent flat joints transferring forces in only Z direction between the BOLD-arm and the mid-shafts.

The flexible cam joint which is used to elevate the BOLD-arm was modelled and meshed in I-DEAS with the exact cam profile. The cam profile was represented by 7 arcs which were defined by the location and orientation of 15 different nodes as shown in Figure 9.

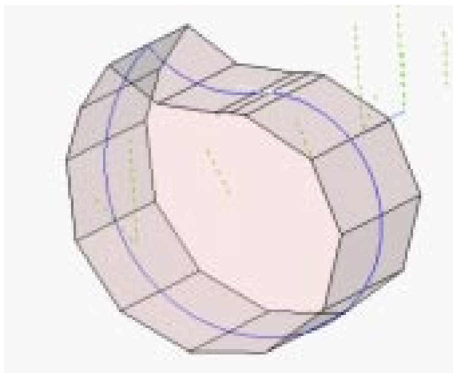

Figure 9 *The CAM profile*

The cam includes a small detent (over centre characteristics) at the fully locked position which ensures the cam will not rotate off (releasing the offload) during launch vibration. The cam joint allow separation and will be further refined to include Hertzian stiffness and stresses. Figure 10 shows the follower elevation caused by the cam detent

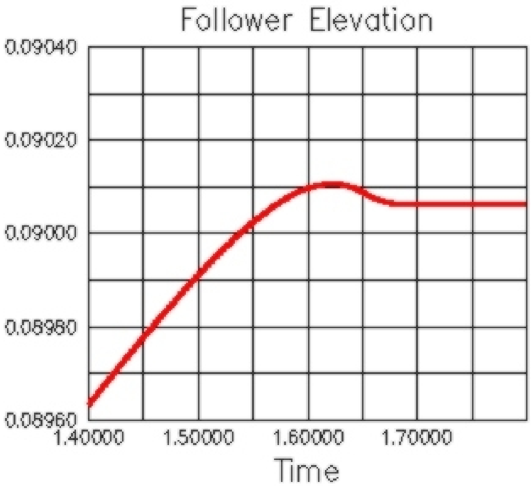

Figure 10 *The Follower elevation / cam detent*

The cam is driven 310 degrees via a motor gear-head assembly which employs two DC brushed torque motors in a tandem configuration. The gear unit is represented by a gear joint (ratio 1:112) and an input stiffness of 0.02 [N/rad]. . The gear-head inertias is also modelled according to the specifications.

The characteristics of the DC motors and the Mechanism Drive Electronics (MDE) is modelled using the FEDEM Control module which is fully integrated with the FEDEM mechanism module. A summary of the MDE is given in Table 2.

Table 2 *MDE characteristics*

MDE characteristics	Symbol	Value
Input voltage source	U	± 37 [V]
Motor Torque Constant	K	0.035 [Nm/Amp]
Motor electrical resistance	R	9 Ω
Motor Back EMF	e	0.035 [V/rad/sec]
Coulomb friction (motor bearings/brushes)	c	0.004 [Nm]
Gear-head efficiency (on-load / offload)	η	0.8 / 0.4
Gear ratio	n	1 : 112
Inertia on high speed side	I	3.0e-6 [kgm^2]
Gear stiffness (input side)	k	0.02 [Nm/rad]
Eddy current damping	ξ	0 (initially)

The FEDEM model of the MDE is shown in Figure 11. Each block is selected from the FEDEM Control icon panel and positioned in a 2D control scheme. The block connections are established by drawing lines between the input and output ports of the various blocks.

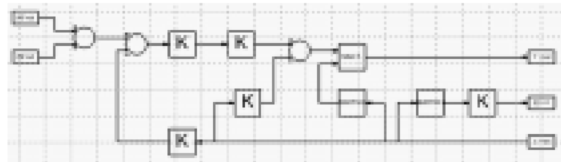

Figure 11 *The MDE control system*

The control system has 2 input and 1 output blocks. The input blocks are the applied voltage source (37 Volts) and a velocity measurement which is connected to a sensor on the GOMOS mechanism model. The sensor is applied on the high speed side of the gear-head and passes the joint velocity to the control system (feedback measurement).

The output block is representing the net generated motor torque applied to the gear-head. This output torque is attached to the torque symbol applied to the actuator link on the GOMOS mechanism model as shown in Figure 12.

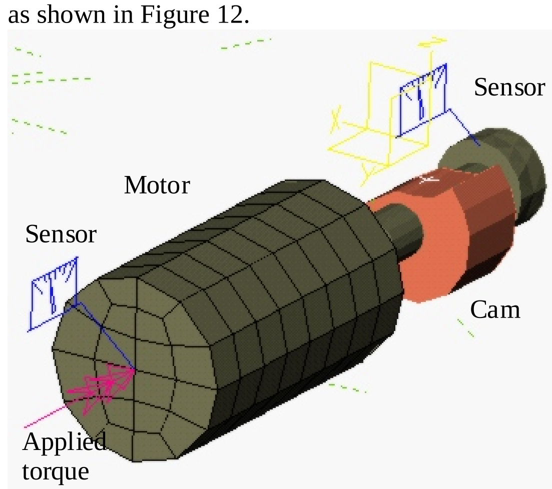

Figure 12 *The applied motor torque*

The coupling between the input/output blocks and the 3D symbols are achieved by using a FEDEM item called an “Engine”. An Engine can use a control block or a sensor output as an argument to a unit scaling function. The value returned by an Engine can then either be an applied force/torque from the control system or a measured variable from the mechanism model.

These multidisciplinary modelling techniques allowed us to create a complete virtual prototype of the GOMOS SFM.

The initial FEDEM model was continuously improved to fit the available measurements. The motor and structural damping/friction properties were as expected the most difficult parameters to measure/identify. Some improvements of the finite element models representing the BOLD-arm and the Turntable Assembly had to be made in order to obtain correct stiffness distribution.

SIMULATIONS AND RESULTS

The simulations were carried out in two steps representing the on-load and offload operations respectively. The on-load simulations were first performed in order to calibrate the GOMOS SFM model against the available measurement. These simulations did not match the physical on-load operation which was carried out manually. Usually the operator applied the strain energy into the SFM by rotating the cam manually.

This does not influence on the amount of final stored strain energy in the SFM. The strain energy does only depend on the overall stiffness of the SFM and the cam elevation in +Z direction which is shown in Figure 13.

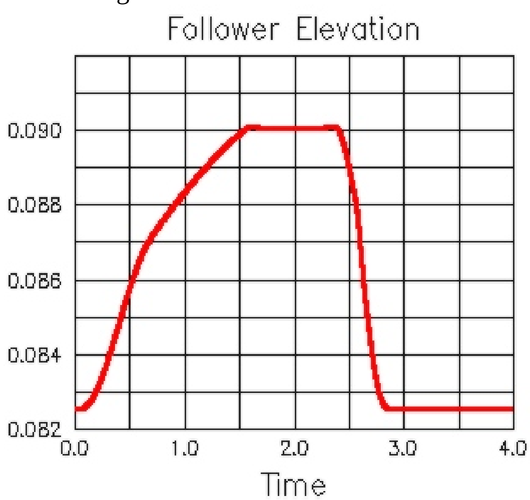

Figure 13 *The Cam elevation*

The on-load simulations did efficiently predict the amount of stored strain energy and reaction forces between the various links in the SFM model. A plot of the stored strain energy in the BOLD-arm and Turntable assembly (dashed line) is shown in Figure 14.

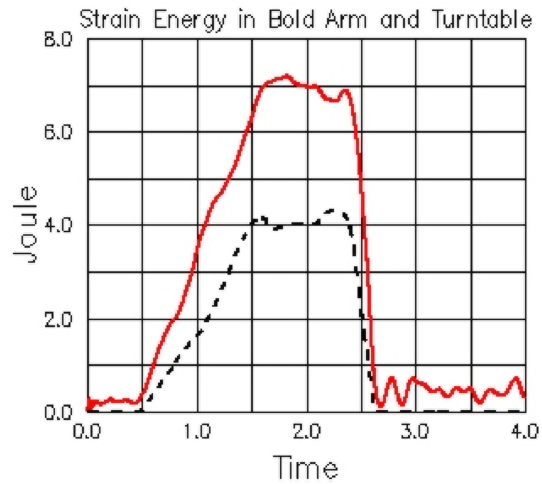

Figure 14 *The applied strain energy*

The off-load simulations were carried out to identify how much Eddie current damping that had to be applied on the redundant motor to avoid damage to any of the mechanical or electrical components. The initial damping due to back EMF is shown in Figure 15. This damping was not sufficient to avoid damage on the GOMOS SFM. More Eddie current damping was then introduced on the redundant motor

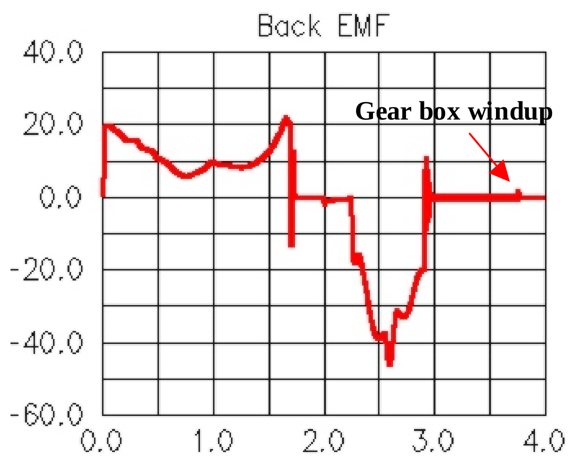

Figure 15 *The initial back EMF*

We also wanted to investigate some of the measured peak values in the redundant motor back EMF (except for the peak values when the cam hits the end-stops). The simulations showed that the torsional gear box flexibility caused a measured back EMF peak after the voltage source was switched off. This was due to a wind up effect / angular deflection of the gear box that caused a rotational acceleration/velocity of the high speed side of the gear box/axles. The back EMF is proportional to the angular velocity and hence caused a sudden increase in the measured voltage as Figure 15 shows.

The stress results were not of great interest in these studies but were used to verify that the element meshes and joints were properly selected with respect to the transfer of reaction forces between the various mechanism links. The stress results did also indicate which structural parts that could have been damaged. Figure 16 shows a snapshot of the stress distribution at a selected time step.

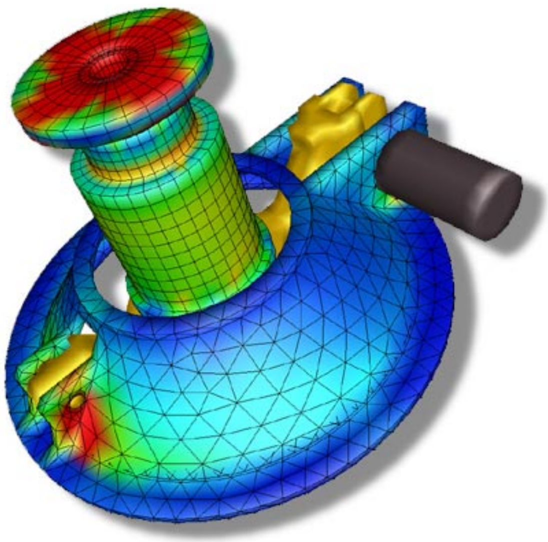

Figure 16 *GOMOS stress distribution*

SUMMARY

In this project the FEDEM software was an enabler which allowed engineers from different disciplines to input their know-how into a single database and solve all variables simultaneously.

The results were very accurate with respect to strain energy distribution, reaction forces, elevation distances and motor back EMF. Parameters describing the free elevation distance, cam profile and the control system could easily be changed to evaluate the performance of the GOMOS SFM.

Some of the solved control variables are difficult to verify due to no access to measurements during the off-load test which damaged the GOMOS SFM.

However, the simulations of the off-load test with no Eddie current damping showed that the peak angular accelerations and reaction forces during off-load were far too high to be accepted.

The simulations also showed that the peak loads during the on-load operation also were unacceptable high if the voltage source (37 V) was on when the Cam was hitting the end stops.

If FEDEM simulations had been performed prior to the off-load test, it would have been possible to predict the accident that damaged the GOMOS SFM. If the project had been more simulation driven the proper amount of damping could have been selected and a safe and reliable off-load test operation could have been performed.

FURTHER WORK

The “SAR Deployment Modelling Project” will be finished in October 99. The GOMOS SFM model as well as the other benchmark modelling examples will be continuously improved and finally documented at the end of the project.

A special effort will be dedicated to improved friction identification and modelling. Both structural damping and coulomb friction are difficult to predict without access to test results.

However, the most critical issues in a project where engineers from various disciplines are involved is communication and reuse of data. To ensure efficient use of multidisciplinary simulation tools like FEDEM, engineers from different disciplines must work closely together and use software tools that are integrated.

A major task in this project has therefor been to develop excellent interfaces between FEDEM and other CAE tools like NASTRAN, PATRAN and I-DEAS.

With these interfaces FEDEM has proven to be an efficient multidisciplinary simulation tool supporting all features required to model and simulate advanced mechanical systems like GOMOS SFM, MIMR RDM, PDM, MHSA and ASAR. Updated reports from these benchmarks are available.

ACKNOWLEDGEMENTS

The authors wish to thank the GOMOS SFM team at Matra Marconi Space and the FEDEM staff that have provided the test results and implemented the new FEDEM features that was required to perform and verify these simulations.

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