1. Scope

This technical note introduces and reports on dynamical modelling and simulation results of a seismic protection system for ELT main structure. The focus here is to verify the feasibility of the concept and the effect it could have on reducing the level of the accelerations on critical units of the telescope during a seismic event. This report explains the concept, the modelling, and simulation results.

2. Concept

It is assumed that each of the 80 pads of telescope support system in outer azimuth ring will be equipped with one of the so called hydraulic seismic protection systems. Each system consists of a hydraulic cylinder filled with oil whose pressure is given by the weight of the telescope at that pad location and the area of the cylinder. The cylinders are connected to two configurations of accumulators through some hydraulic lines and valves, here called configuration A and B. The accumulators are preloaded with nitrogen gas (see HYDAC hydro-Blasenspeicher for technical info for accumulators). The difference of gas pressure and the oil pressure in the cylinder defines the force threshold for oil release in the accumulators. Configuration B accumulator is a modified version of standard configuration A accumulator to accommodate a negative pressure/force threshold for cutting large accelerations in opposite direction.

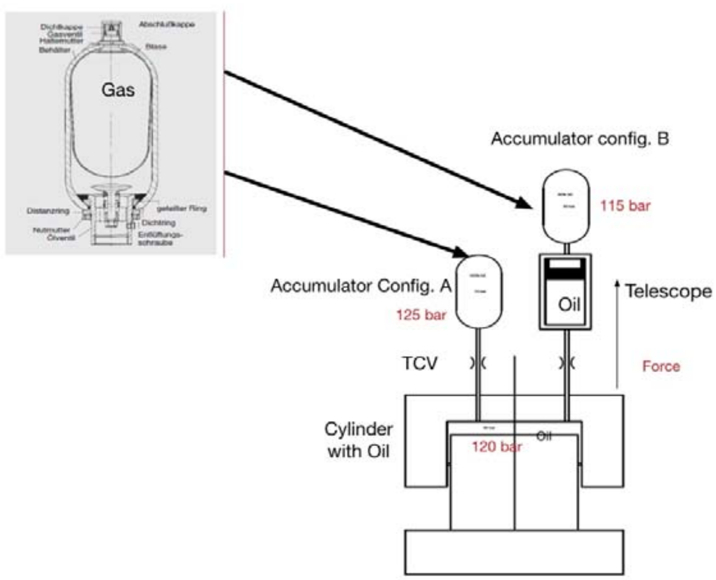

Figure 1 Seismic hydraulic protection system concept: cylinder, valves and accumulators

The main idea of the seismic protection system is to change dynamically the stiffness between the telescope pier and the structure (reduce stiffness) and to filter out high accelerations generated by a seismic event at interface to the telescope structure. This is realized by changing the oil volume in the hydraulic cylinders. Variation of oil volume or pressure, changes the force transmitted to the telescope structure. Oil is released when a force threshold is reached (upper pressure for configuration A accumulator and lower threshold level for configuration B accumulator). Technically, the force threshold is defined by the nitrogen pressure preload of the accumulators, which are connected to the hydraulic circuit by check valves (TCV = throttle-check valve). The accumulated oil in configuration A is returned to the cylinder and to accumulator configuration B during the low pressure (low acceleration) and during the high-pressure regime the opposite happens. The return flow is limited by the throttle of the TCV.

From a dynamic point of view releasing oil into accumulators is equivalent to a change of stiffness of the hydraulic cylinder. The stiffness/force switches dynamically between the stiffness/force of the closed hydraulic system and the stiffness of the nitrogen reservoir of the accumulators. The performance and efficiency of the system depends on some design parameters which are mainly the size of the cylinder, accumulators and the differential or pressure threshold between the oil and gas in accumulators. Figure 1 shows a schematic of the concept for one pad of the telescope azimuth support.

3. Modelling

The Main structure earthquake protection system described in the last section is modelled and simulated using Matlab/Simulink. The model itself is composed of two main elements: 1) The model of hydraulics including pad cylinders, pipes, accumulator and throttle-check valves. 2) The telescope structure is modelled i) once with a lumped mas/spring representing the equivalent mass seen by one of the supporting pads, i.e. $1/80^{th}$ of telescope mass and representing the first eigenmode of the telescope, and ii) once by the complete FEM representing all modes and mirror unit 6DOF motions. These elements are introduced more in detail in the next section

3.1 Model of the Hydraulic System

The telescope structure is supported vertically on the azimuth outer ring using 80 hydrostatic pads. The idea is that each vertical support pad is equipped with one of the hydraulic system represented in Section2 . The hydraulic system for each pad is modelled by:

- A piston cylinder representing the oil volume. The cylinder model uses the oil flow, the position and velocity of the piston (cylinder) to compute the resulting force transmitted to the interface of the telescope model. The compressibility of the oil is used to represent the physical phenomenon.
- The pipes models represent three effects of i) the compressibility of the oil, ii) the friction of the pipe to limit the flow or to generate a pressure drop, iii) the dynamic effect of the varying flow using the inertial properties of the oil volume.
- There are two configurations of accumulators as presented in the concept. These are in general modelled as gas volumes, in one configuration they can be compressed and for the other configuration they can be expand. In one case the expansion is constraint and for the other case the compression is constrained. In both cases the pressure change is modelled by the adiabatic gas equation: $P_{BS} = P_0(\frac{V_{BS}}{V})^{1.4}$. The inlet and outlet flow characteristics of the valves, i.e. flow as a function of differential pressure, are defined based on same lookup tables. The tables are used from the data sheet of some manufacturers (here Boch Rexroth). See Section 4 for detailed parameters and

values. The details of the modelling principle of the compressed accumulators and valves can also be consulted in [‘Additional Damping System for ALMA Antenna Transporters: Dynamical analysis report, ANTD-37.08.00.00-002-A-REP’]. The model of the compressed accumulators and valves are modified such that it represents the behaviour of an expansion accumulators which is designed for isolating the system for the lower half of the disturbance wave.

3.2 Model of the telescope mechanical structure

The hydraulic system is interfaced to the mechanical structure through two interface signals: i) the forces generated by the hydraulic cylinders, ii) the position (differential) and speed of the telescope base. The later are fed to the hydraulic cylinder (input to cylinders) and the former (output of the cylinder) is applied as input to the telescope structure at the location of telescope azimuth outer ring, i.e. pads locations.

Two mechanical models are used to study the effect of the protection system: First, telescope structure is represented by a lumped mass spring system to simplify the problem, reduce the computations and potential numerical issues and to focus on the principle of the hydraulic concept itself. Second model assumes the complete FEM of the telescope structure representing the dummy mirrors and their 6DOF motions. The latter model is used to verify the level of the motions/accelerations at sensitive unit locations, e.g. M1, M2, during earthquake before and after the protection system activated. The two mechanical model concepts are defined as follows:

Proof of concept: telescope represented by a lumped mass spring system

To show the functionality of the concept and to focus on the hydraulic behaviour and to recued the calculation complexity, in the first step the telescope is modelled by two lumped mass and a spring system. The model assumes only one pad or protection system, consequently it is assumed to act on 1/80th of the telescope mass. A parametric model is constructed where the values of two mass, one representing the base and the second the telescope structure, and the spring can be tuned such to vary the principle oscillation mode of the telescope, e.g. 3 or 4Hz.

The mass/spring system receives the force from the hydraulic cylinder as input (force to the base mass) and provides the difference motion of the ground and the base (as well as the speed) to the cylinder. The parameters of the mass/spring, the hydraulic system and the simulation results are given in detail in Section 4.

Detailed model: telescope represented by FEM

The complete simulation involves the FEM of the telescope structure. The FEM model of the telescope expressed in state-space format with appropriate inputs and outputs are used for the detailed simulation of the earthquake protection system. The model represents 200 modes (400 states) of the structure up to 20Hz. The main outputs of the model are the differential motion of the cylinders at location of the 80 pads, and motions of the telescope mirrors. The inputs to the model are the forces at the telescope interface to the pier (80 forces at pad locations), and the ground motion in three x, y and z directions. In this study, the vertical acceleration input is used for introducing the ground motion due to an earthquake. However, the model copes with other two directions inputs as well. The ground acceleration/and motion time series characteristics are detailed in Section 4.

3.3 Combining the hydraulics with mechanics

Matlab/Simulink is used to realize and combine the hydraulic system and telescope mechanical structure models presented earlier. Figure 2 shows the block-diagram of the combined system and the main subsystems, namely telescope structure model, hydraulic cylinder, hydraulic lines, and accumulator configuration A and B. Figure 3 depicts the model and block-diagram of an accumulator including the model of the valves. Hydraulic cylinder model is shown in Figure 4. The hydraulic line model diagram defining the compliance and intertance are shown in Figure 5.

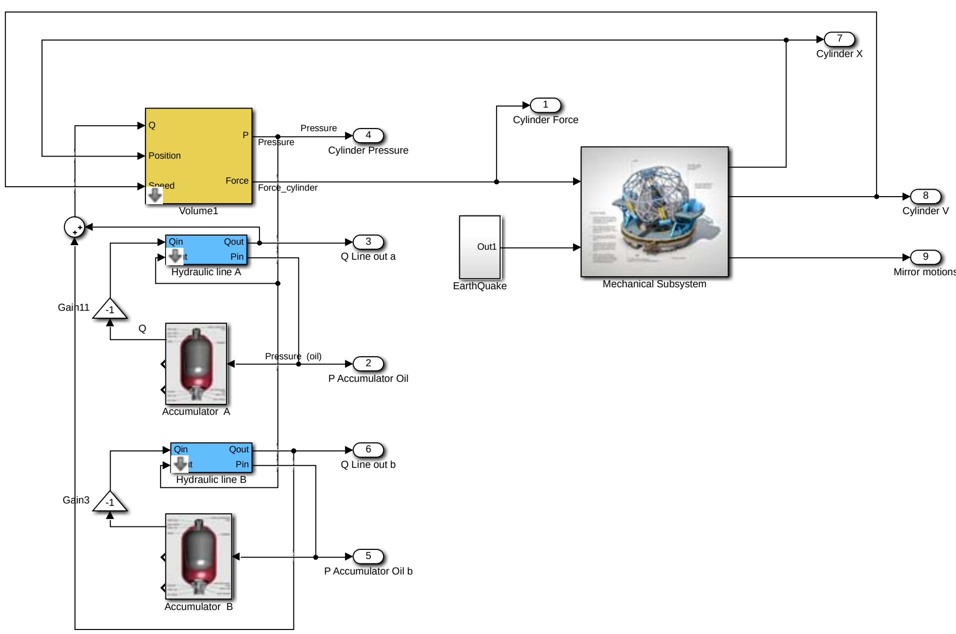

Figure 2 Complete system modelling and simulation block-diagrams

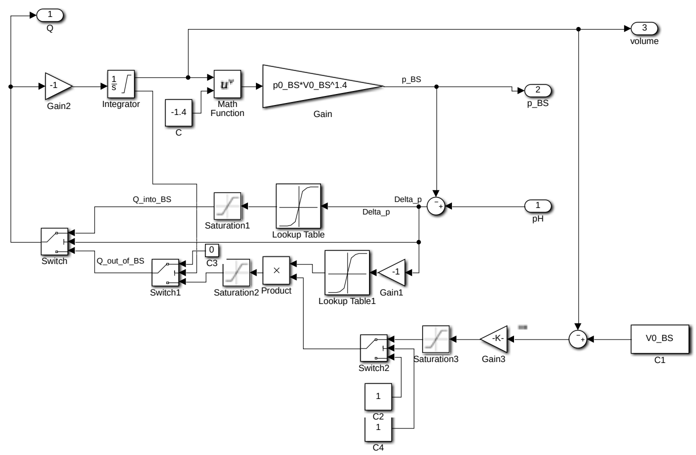

Figure 3 Accumulator A: model block-diagram

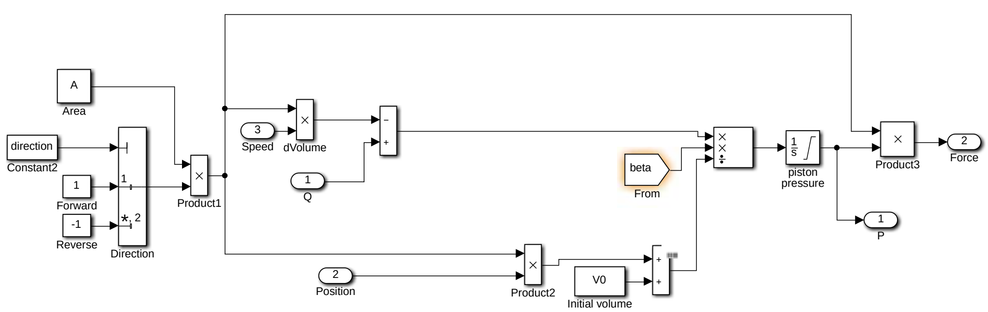

Figure 4 Cylinder model

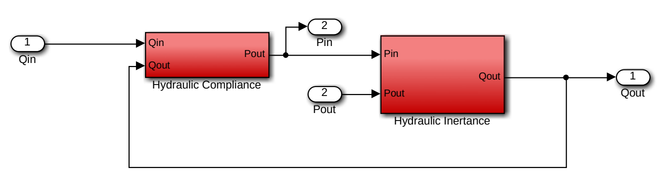

Figure 5 Hydraulic line model diagram

4. Design Parameters and Simulation Results

4.1 Design and simulation parameters

The parameters used for dimensioning (nominal case) and simulation of the complete system are summarized as below:

Table 1 Design and simulation parameters of the hydraulics system

Initial oil pressure of each cylinder: P_0	120 [bar]
Ambient temperature (for oil characteristics)	9 [deg]
Cylinder area and diameter: $M_{tel} * g/P_0$ * beta	0.028[m^2], 0.19 [m]
Initial volume of Cylinder (oil): area * 0.2	0.0056 [m^3]
Pipes lengths	1 [m]
Pipes diameter	0.0762 [m] (3 inch)
Initial nitrogen pressure of accumulator A (compressed accumulator)	125 [bar]
Initial nitrogen pressure of accumulator B (decompressed accumulator)	115 [bar]
Initial Cylinder (oil) pressure	120 [bar]
Initial Volume of accumulator A and B	18.4 e-3 [m^3]
Characteristic of None Reversible Valve (NRV) for accumulator A (inlet) and B (outlet)	See Table 3
Characteristic of Throttle valve for accumulator A (outlet) and B (inlet)	See Table 2

Table 2 Characteristics of the throttle valves (accumulator A and B) LUT

Pressure [P]	0.1e5	0.5e5	1e5	2e5	3e5	4e5	5e5
Flow [m^3/min]	13e-3	35e-3	52e-3	77e-3	95e-3	110e-3	125e-3

Table 3 Characteristics of the NRV valves (accumulator A and B) LUT

Pressure [P]	0.25e5	0.5e5	0.9e5	1.2e5	2e5	3e5
Flow [m^3/min]	30e-3	75e-3	150e-3	225e-3	300e-3	375e-3

Table 4 Telescope mechanical system parameters for lumped mass spring assumption

Total moving mass (Telescope mass/80 = Mt) [kg]	Base mass Mt_1 [kg]	Flexible mass Mt_2 [kg]	Telescope main resonant frequency [Hz]	Damping factor
3.45e6 /80 = 43125	0.2* Mt = 8625	0.8*Mt = 34500	4	0.01

In the complete system simulation as described Section 3.2 the FEM model of the telescope structure is used. This model, amongst other inputs, has three inputs for the seismic excitations. For this reason, the complete model is mounted on a large mass (1e4 times the telescope mass with pier of about 20e3 tons) and a spring, which gives the first 3 eigen-frequencies of about 0.02Hz. The input is a force scaled to the mass, so at higher frequencies (above the 0.02Hz resonance the acceleration for a unit input is 1 m/s^2. At the location of vertical support system, the model accepts input forces (80 pads) which are the interface point to the hydraulic damping system.

4.2 Simulation Results

The ground acceleration/motion due to an earthquake (the input to the models) is assumed to be time histories derived from real seismic events properly scale. For the simulation results, here a vertical acceleration time series (NCR case) from ESO-242434 (TH_NCR_12_Z) is used. Figure 6 shows the acceleration time series used as an excitation to the system.

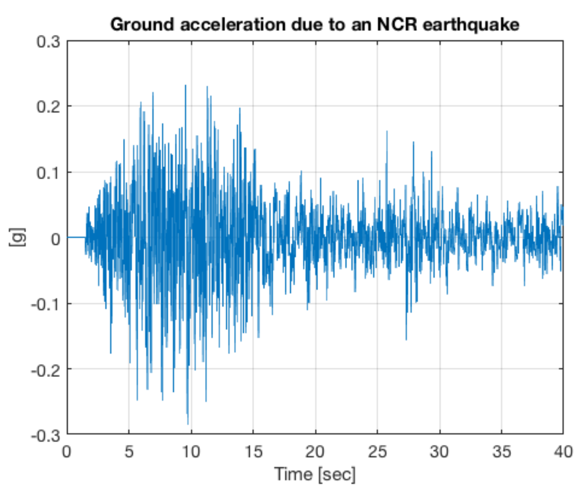

Figure 6 Ground acceleration in Z direction due to a NCR earthquake

4.2.1 Mechanical system using a lumped mass/spring: proof of concept

The seismic protection device connected to a mechanical system representing a telescope with equivalent mass and stiffness as a lumped mass/spring is simulated subject to the ground acceleration/motion presented above. First, the system was assumed to be turned off, that is no oil flow from cylinder to accumulators. Figure 7 shows the accelerations from ground, telescope base (first mass) and telescope (second mass) and their respective Power Spectra Density (PSD). The motions are depicted in Figure 8. From the spectra, the amplification of the acceleration/motion (@ 4Hz) on the mass representing the telescope can be observed. A ground acceleration of 0.06 [g] rms is amplified up to 0.27 [g] rms mainly at 4Hz.

The system is simulated for the case when the hydraulic system is active. Figure 9 and Figure 10 show respectively the accelerations and motions when the system is active. It can be seen that in this case the acceleration at resonant frequency is considerably attenuated, and the total acceleration at telescope level (second mass) is reduced to 0.04 [g] rms.

The base motion spectra reveal that the accelerations are automatically notched out at the resonant frequency, therefore at the telescope level the motion at this frequency is attenuated.

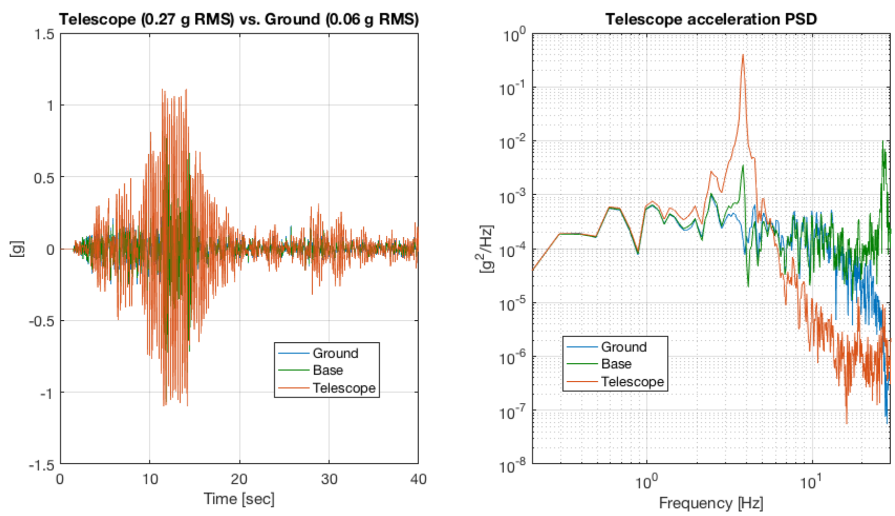

Figure 7 Seismic system off (No flow to accumulators and into cylinders): Acceleration temporal response (left) and PSD (right). Ground (blue), Telescope base Mt_1 (green), Telescope Mt_2 (red)

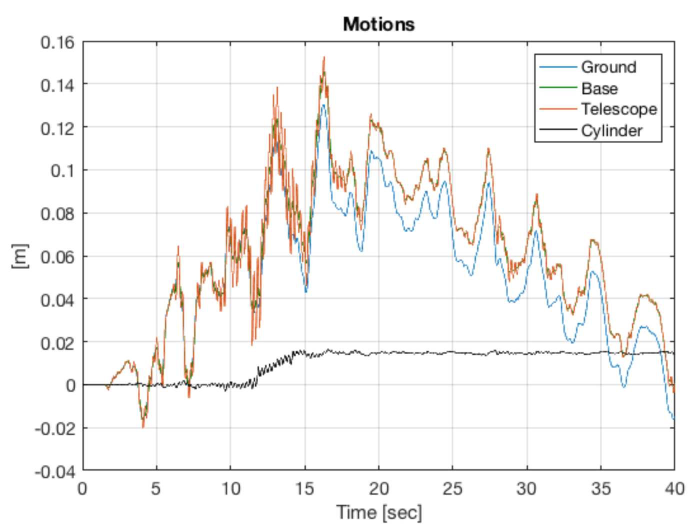

Figure 8 Seismic system off (No flow to accumulators and into cylinders): Motions temporal response. Ground (blue), Telescope base Mt_1 (green), Telescope Mt_2 (red)

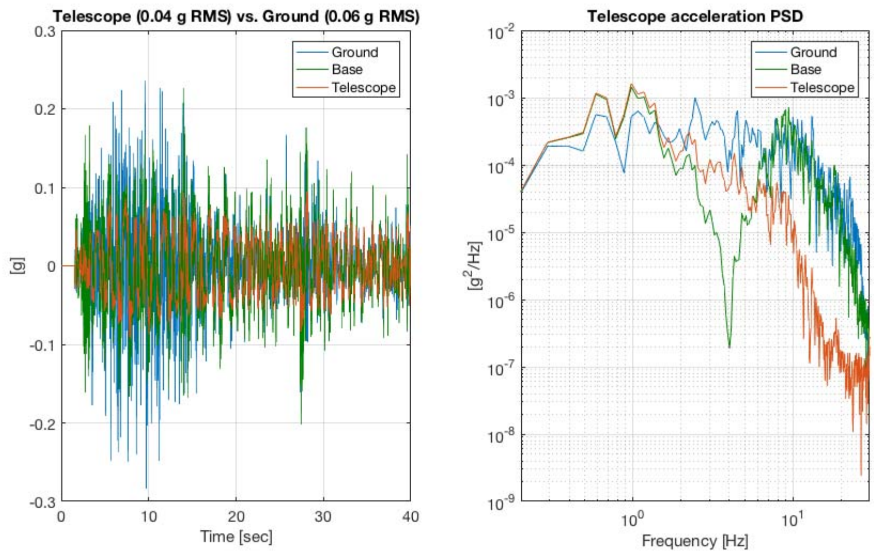

Figure 9 Seismic system on: Acceleration temporal response (left) and PSD (right). Ground (blue), Telescope base Mt_1 (green), Telescope Mt_2 (red)

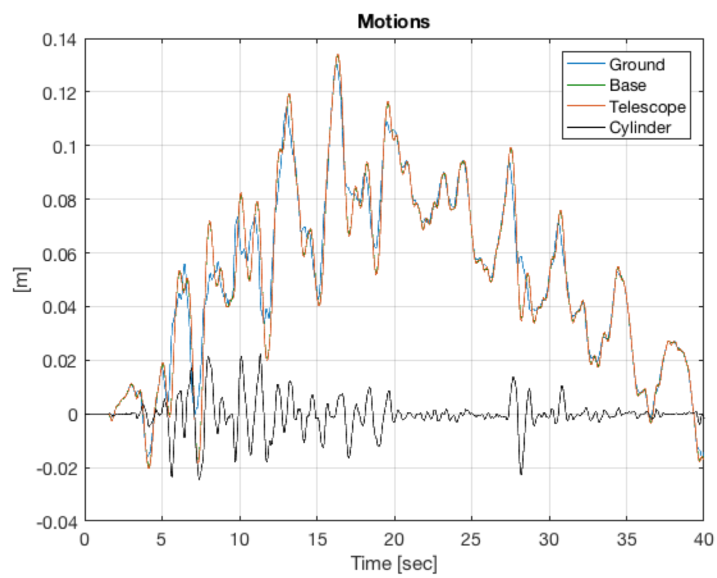

Figure 10 Seismic system on: Motions temporal response. Ground (blue), Telescope base Mt_1 (green), Telescope Mt_2 (red)

Figure 11 shows the pressure of oil and gas in accumulators configuration A and B. The oil flow into and out of these accumulators are shown in the same figure. As the oil pressure increases (decreases) higher (lower) than the threshold the gas pressure in accumulators increases (decreases). The gas volume in accumulator A decreases and in the case of accumulator B the volume increases and it pushes the piston in this accumulator to move down pushing the oil out of the accumulator B.

The dynamic force of the cylinder (applied to the telescope) is shown in Figure 12.

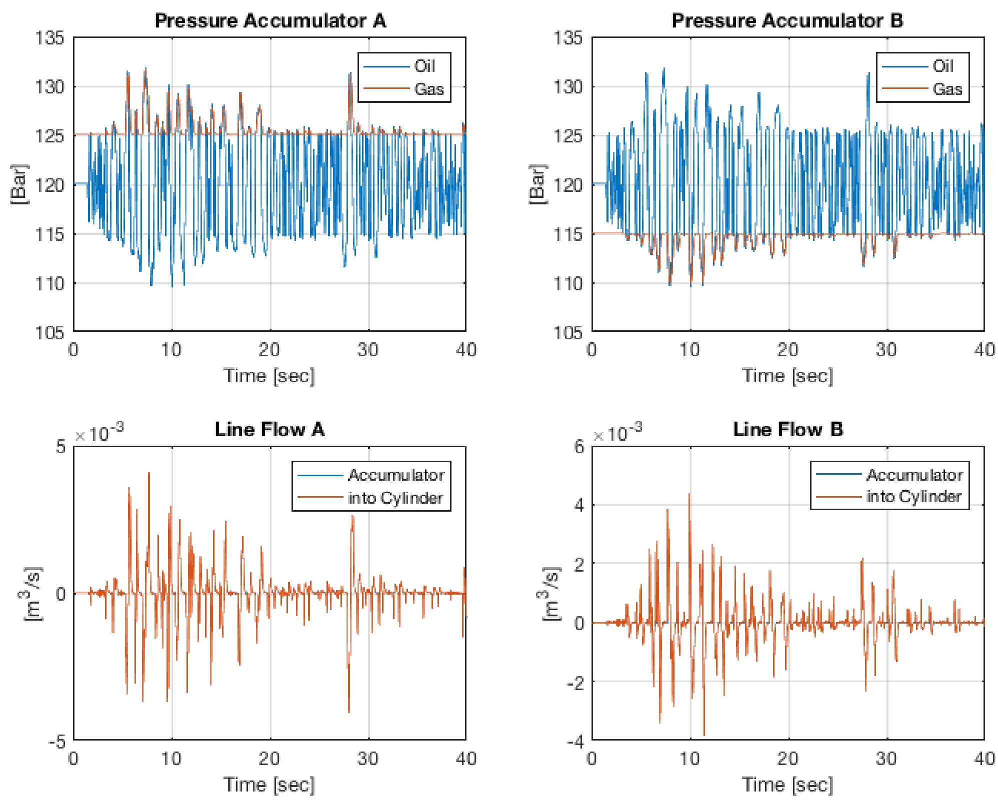

Figure 11 Seismic system on: Oil and Gas pressures in accumulator A and B (above), Oil flow in hydraulic line to cylinder and accumulator A and B (below)

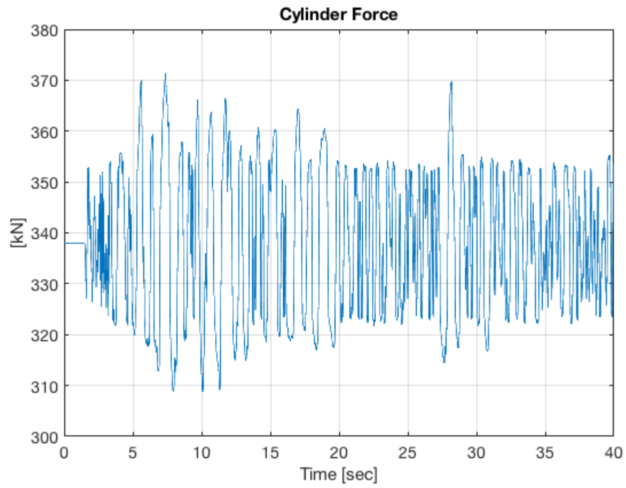

Figure 12 Cylinder Force (applied at each pad to telescope)

Figure 13 compares the acceleration time series and their PSDs at telescope level before and after the hydraulic system is active.

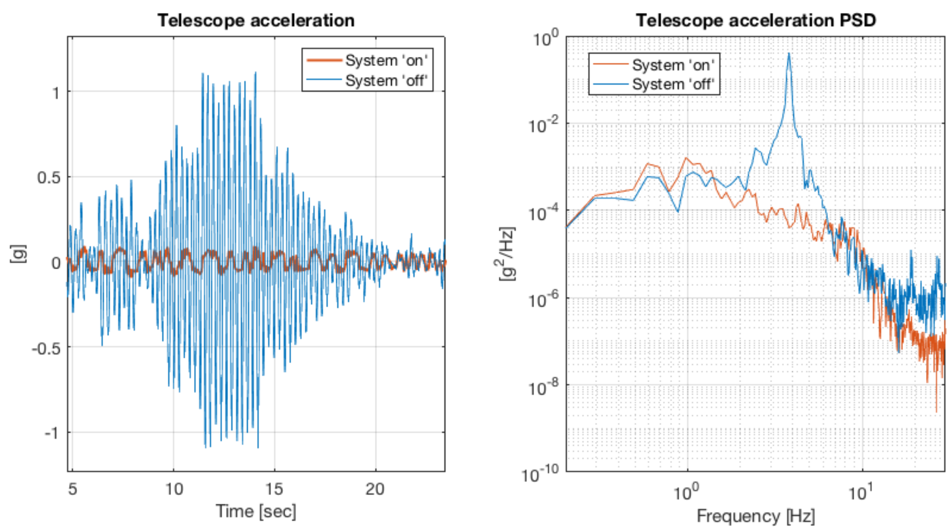

Figure 13 Telescope Mt$_2$ acceleration, system off (blue), system on (red)

4.2.2 Mechanical system using FEM: detailed results

The simulation and analysis of the simplified system helped to understand the behaviour of the system and to set the important parameters of the hydraulic system. It was also crucial at the beginning of the analysis, to identify the potential numerical issues and to avoid long and heavy calculations before understanding the efficiency of the approach and concept itself.

In the second step of analysis, the simulation is extended to the full FEM of telescope assuming 80 pads where the protection system is implemented. The assumptions were presented earlier in this technical note. The complete system with the same set of parameters of the simplified system is simulated for two cases of hydraulic system off and on respectively.

Figure 14 shows the accelerations from ground, telescope base and M2 unit z direction, and their respective Power Spectra Density (PSD). The motions are depicted Figure 15. From the spectra, the amplification of the acceleration/motion at telescope level (M2 unit) can be observed. A ground acceleration of 0.06 [g] rms is amplified up to 0.51 [g] rms mainly at 5Hz at M2 unit level. The amplification at other frequency modes related to M2 can also be observed.

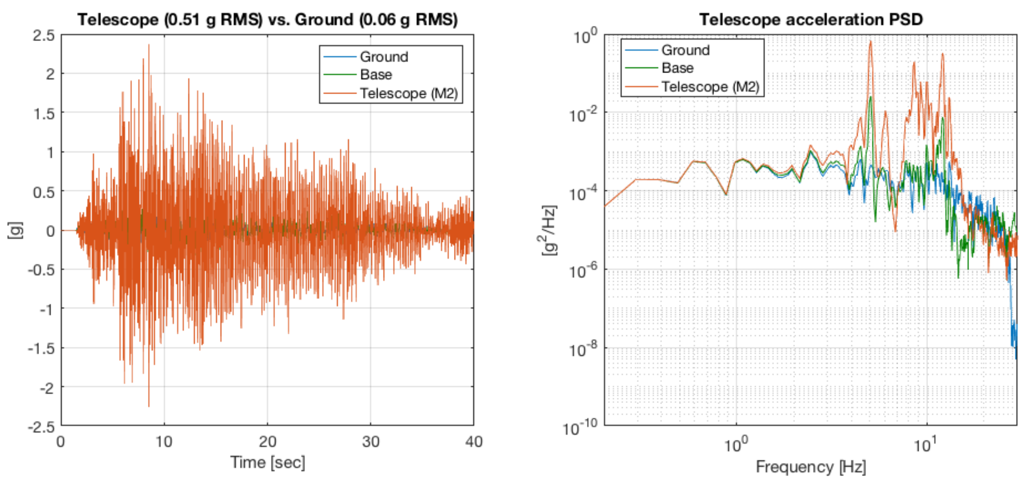

Figure 14 Seismic system off (No flow to accumulators and into cylinders): Acceleration temporal response (left) and PSD (right). Ground (blue), Telescope base (green), Telescope mirror M2 (red)

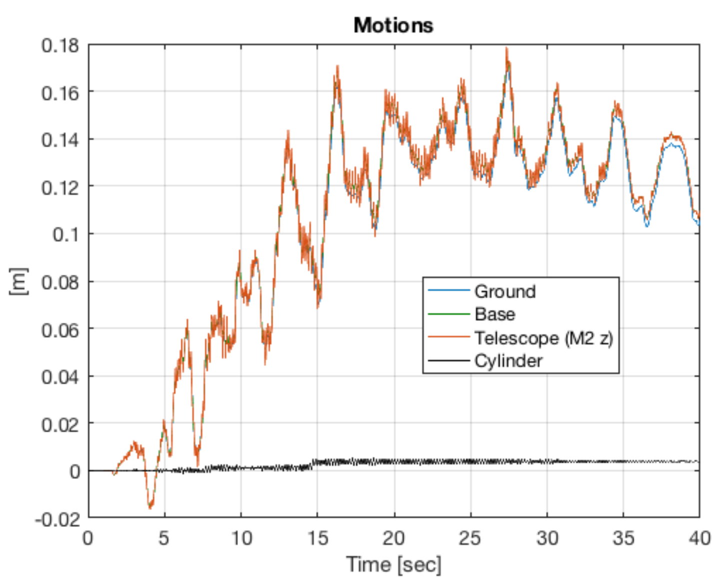

Figure 15 Seismic system off (No flow to accumulators and into cylinders): Motions temporal response. Ground (blue), Telescope base (green), Telescope mirror M2 (red)

The system is simulated for the case when the hydraulic system is active. Figure 16 and Figure 17 show respectively the accelerations and motions when the system is active. It can be seen that in this case the acceleration at resonant frequencies is considerably attenuated, and the total acceleration at telescope level (M2 unit z direction) is reduced to 0.09 [g] rms.

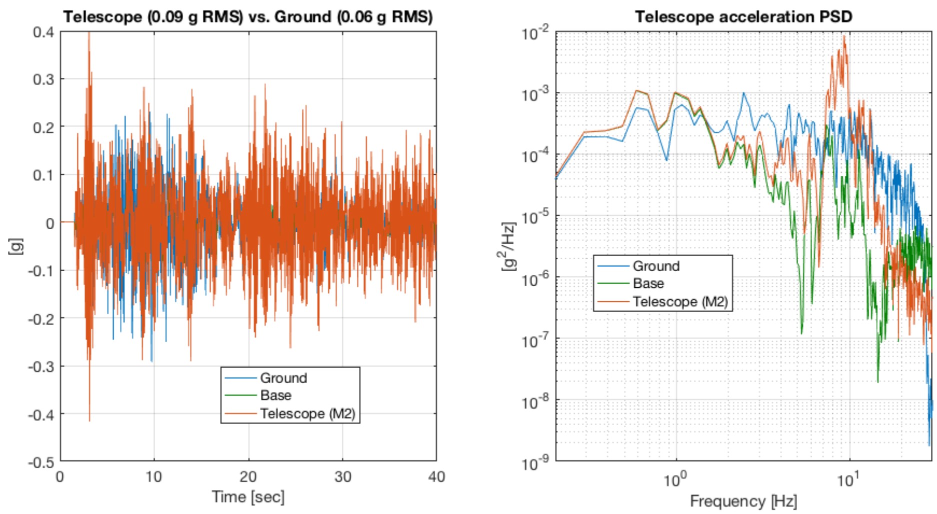

Figure 16 Seismic system on: Acceleration temporal response (left) and PSD (right). Ground (blue), Telescope base (green), Telescope M2 z (red)

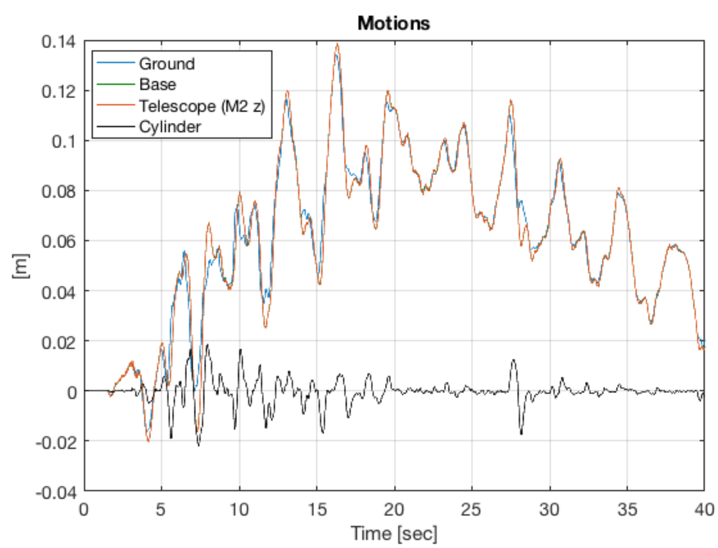

Figure 17 Seismic system on: Motions temporal response. Ground (blue), Telescope base (green), Telescope M2 z (red)

Figure 18 shows the pressure of oil and gas in accumulators configuration A and B. The oil flow into and out of these accumulators are shown in the same figure. Similar behaviour as in the case of the simplified system simulation can be seen. Just as it can be expected, the flow and pressure are subjected to different and multiple frequencies due to interfacing to the complete telescope structure with multitudes of resonant modes.

The dynamic force of the cylinder (applied to the telescope) is shown in Figure 19.

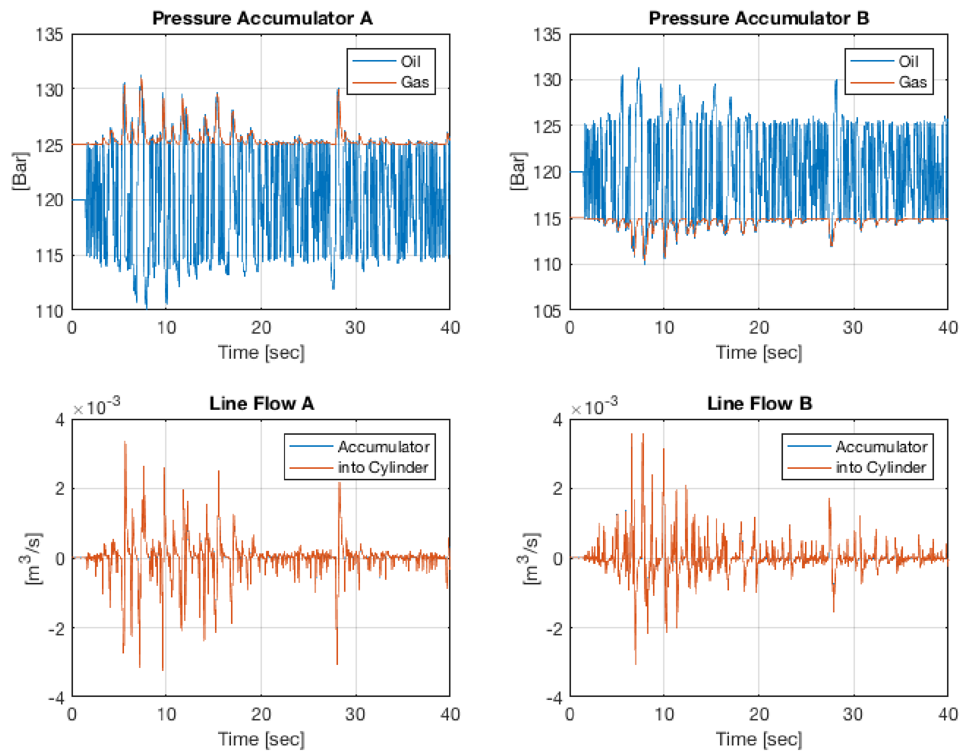

Figure 18 Seismic system on: Oil and Gas pressures in accumulator A and B (above), Oil flow in hydraulic line to cylinder and accumulator A and B (below)

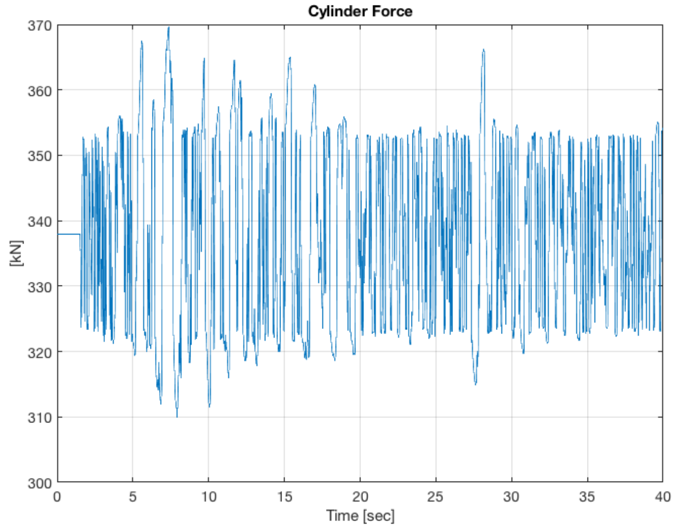

Figure 19 Cylinder Force (applied at each pad to telescope)

Figure 20Figure 13 compares the acceleration time series and their PSDs at telescope level (M2 unit z) before and after the hydraulic system is active.

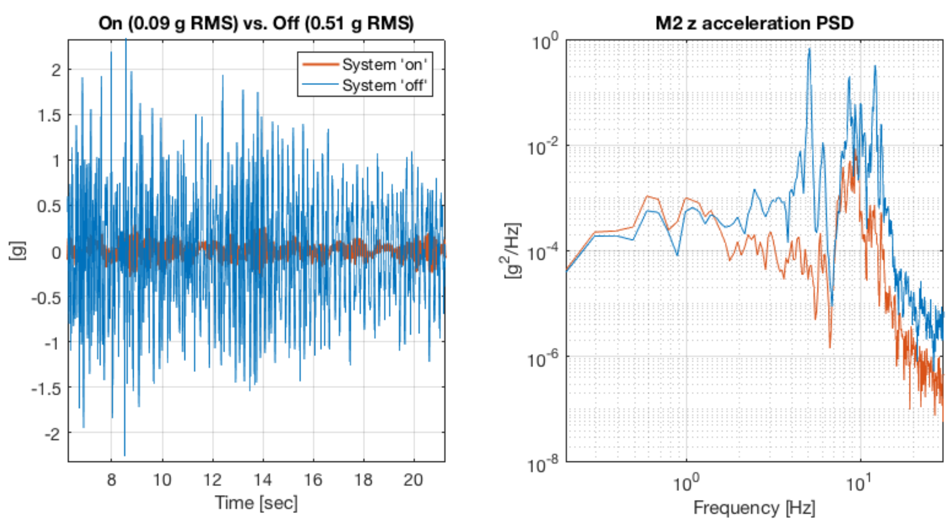

Figure 20 Telescope M2 mirror z acceleration, system off (blue), system on (red)

The FEM provides the motions at any desired location of the telescope. Figure 21Figure 13 compares the acceleration time series and their PSDs at telescope level (M1 unit z) before and after the hydraulic system is active.

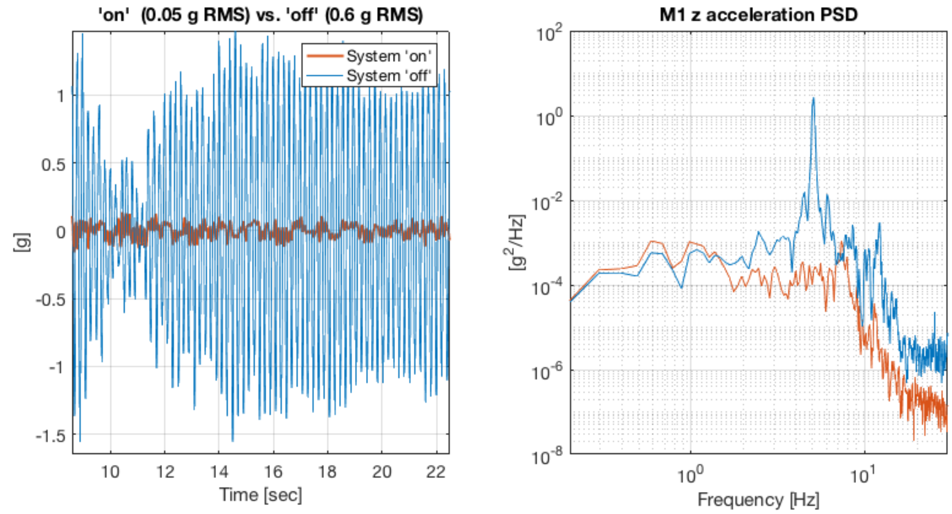

Figure 21 Telescope M1 mirror z acceleration, system off (blue), system on (red)

4.2.3 Effect of some key design parameters

Different important design parameters can be varied and a sensitivity analysis can be done to fine tune the potential final design or to cross-check the imperfection that in real system could potentially affect the functionality or efficiency of the concept itself from one side and operation and performance of the telescope itself from the other side.

One important parameter is the pressure/force threshold of the accumulators, namely the difference between the initial oil pressure in the cylinder and the implemented gas pressure for accumulators. The reason is that due to track/structure inhomogeneity the oil pressure is not the same for all the pads. Hence, the difference between the gas pressure set for the accumulators and the oil pressure can be either low (so that even for normal motion of the telescope and without any high acceleration due to seismic event the oil flows in to accumulators) or high (so that the efficiency of protection might be reduced). To verify the sensitivity of the performance results, the complete system is simulated for three set of threshold values, namely 5, 15 and 25 bars.

Figure 22 shows the accelerations of M1 z for these three cases where the rms values change from 0.05 [g] to 0.1 [g] and 0.14 [g] respectively. However, note that in case of 25 [bar] threshold value there are considerable attenuation observed compared to the case the system is turned off, i.e. 0.14 [g] rms vs. 0.6 [g] rms.

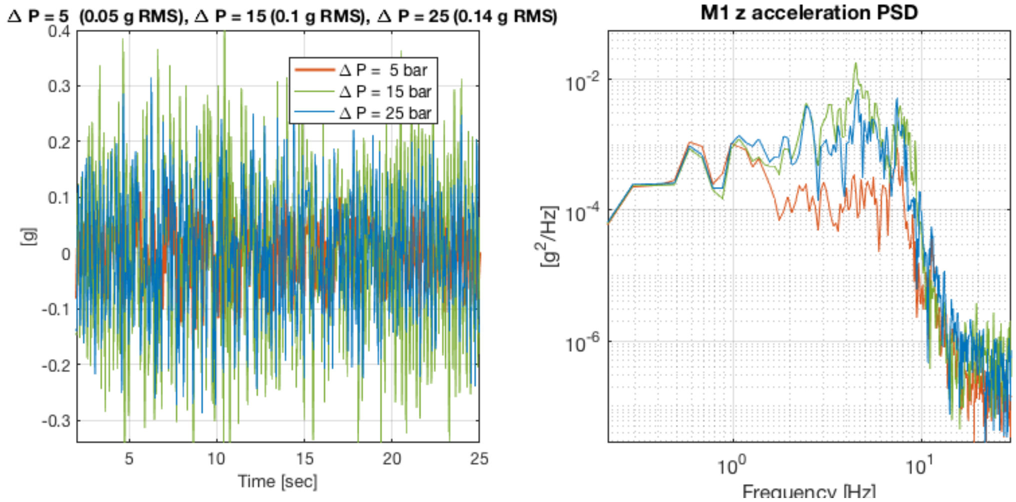

Figure 22 Effect of accumulators' force (pressure) threshold on damping efficiency