OWL: FIRST STEPS TOWARDS DESIGNING THE MECHANICAL STRUCTURE

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Abstract

The design, fabrication and assembly of the supporting structure of a 100-m class telescope is one of the major challenges of the OWL project. The structure must provide sufficient bandpass for the motion control system as well as the required tracking accuracy and dimensional stability under varying thermal and wind loads. The achievable limits of structural eigen-frequencies impose that image stabilisation be implemented downstream in the optical train. We elaborate on different approaches and preliminary solutions, discuss the option of a wind screen to allowing protection but without preventing flushing of local air, the use of damping systems to reduce vibration amplitudes, as well as use of advanced materials. Last but not least, particular attention is paid to costs. Guidelines are set to minimise fabrication, transport, handling, integration and maintenance efforts.

1. Introduction

The mechanical structure shall be seen as a "*skeleton*", which supports all the sub-systems of the telescope. The demonstration of its feasibility is therefore one of the major steps to be performed at the very beginning of the project. We include no speculations on future technological developments which could lead to unknown risks or budget increases.

This approach can be summarised in the following question:

Can we build a rotating support structure for a 100-m reflecting optical system today?

The first step to answer this question is to detect, define and quantify the parameters (*problems*) which are related to the project. Some of these parameters are already well defined and they can be easily quantified. These can be for instance:

- Constrains (e.g.: Optical design)
- Requirements (e.g. Sky coverage)
- Analogies, extrapolations and conjectures, coming from previous experiences in telescope construction.

Other parameters are hidden or not clearly defined. Nevertheless they cannot be neglected because in most cases they reflect the unwritten know how of people who have gained expertise in this specific field over many years of work.

Therefore, bad feeling, worries and concerns must also be quantified.

Once the basic parameters have been collected, we are able to proceed to **the second step,** namely the classification of those parameters. Now the classification methodologies can be various (e.g. budget, criticality, chronological, disciplines, etc.) and all can work well. We have chosen to classify the parameters by domains. This means that for each parameter we have to find out where and when they appear and how they can influence the design. Finding domains for each parameter is a way to assessing and controlling their impact on the project.

The third step is rather straightforward; we have to define a strategy that can cope with the problem. More clearly formulated is "What to do?".

Once "what to do" has been defined and agreed, comes **the fourth step**, the most awkward and less forgiving: "How to do it?". This means defining a hardware solution to solve the problem.

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2. Design guidelines

Table 1 summarises with key words the **first 3 steps** of the design strategy.

Domain	**Problems**	**What to do**
Environment (Site)	Earthquakes. Wind. Solar radiation. Dust. Rain, Snow and Fog. Overall dimensions.	Maximise the stiffness Minimise the wind-exposed area. Wind shield. Covers. Reduce solar absorption on exposed surfaces. Dust rejecting concept. Enclosure. Minimise the overall dimensions of the complete observatory.
Subsystems	Optical elements. Optical path. Re-centering system. Control. Passive Damping. Thermal Control. Drives. Auxiliary drives. Bearings. Cabling and Piping. Mirror covers. Cleaning units. Mirror handling. Instrument handling. Human access. Metrology system.	Integrated design, definition for each sub-system: ▪ Location. ▪ Volume. ▪ Mass.
Structural Parts Material	Dimensional instability Dynamic and static performances. Thermal expansion. Affordability.	Minimise the stresses (microyield strength) Run in. Differentiated parking positions. Specific modulus Mild Steel Composites
Large Optics Material	Suitability (polishable, etc) Dimensional stability. Homogeneity Thermal expansion. Dynamic and static performances due to the mass. Affordability.	Zerodur SiC
Control.	Friction Wind load.	Minimise the friction Maximise the stiffness. Drives. Bearings. Wind screen. Passive damping.

Thermal Control	Solar Radiation Energy consumption. Thermal inertia.	Covers, Shields, Sun Umbrellas, Igloo Enclosure. Surface treatment. “Warm blood” cooling system.
Fabrication	Affordability	Material choice Modular design. Mechanical tolerances. Commercial available parts. Maximise the number of potential Contractors. Minimise the gap between Design Phase and Fabrication Phase
Transportability	Oversized pieces. Access to the site Affordability	Modular design Max 2,4 m x 2,4m x 6 or 12m Max 20 Tons Fabrication on site
Assembly on site	Hoisting facilities Alignment. Safety.	Modular Design. Minimise the mass of each part. Self-machining structure. Self-supporting structure.
Operation	Sky coverage Change of modes. Energy consumption. Manpower resources. Safety.	± 60 degrees from zenith. Minimise the time between: ▪ Stand by mode. ▪ Operation mode ▪ Safety mode. Low mass. High number of automatism.
Maintenance	Down time. Manpower resources. Accessibility Large Optics handling Instrumentation. Cleaning. Safety.	Altitude rotation ± 90 degrees from zenith. Handling facilities. Cleaning facilities. Parking positions. Component standardisation.

Table 1. Design guidelines, first three steps

This table is a design tool, which helps the designers to evaluate and control all the parameters involved on the project, to evaluate quickly new ideas and criticisms.

For instance we can notice that:

- Some problems have more then one domain; they appear several times during the project.
- Curing one problem can also solve another problems (e.g.: maximise the stiffness ⇒ minimise the mass ⇒ low thermal inertia).
- Curing one problem can worsen another (Minimise the wind exposed area ⇒ low external surfaces ⇒ high thermal inertia).

3. Design description

Step four: Definition of a hardware, which shall solve the problems.

The understanding and the application of the methodology behind table 1, leads to the definition of a coherent hardware. The figure 1 shows a possible result of this design process. This mechanical structure is the current baseline concept for the OWL telescope with the OWL *6-mirrors optical design* [1].

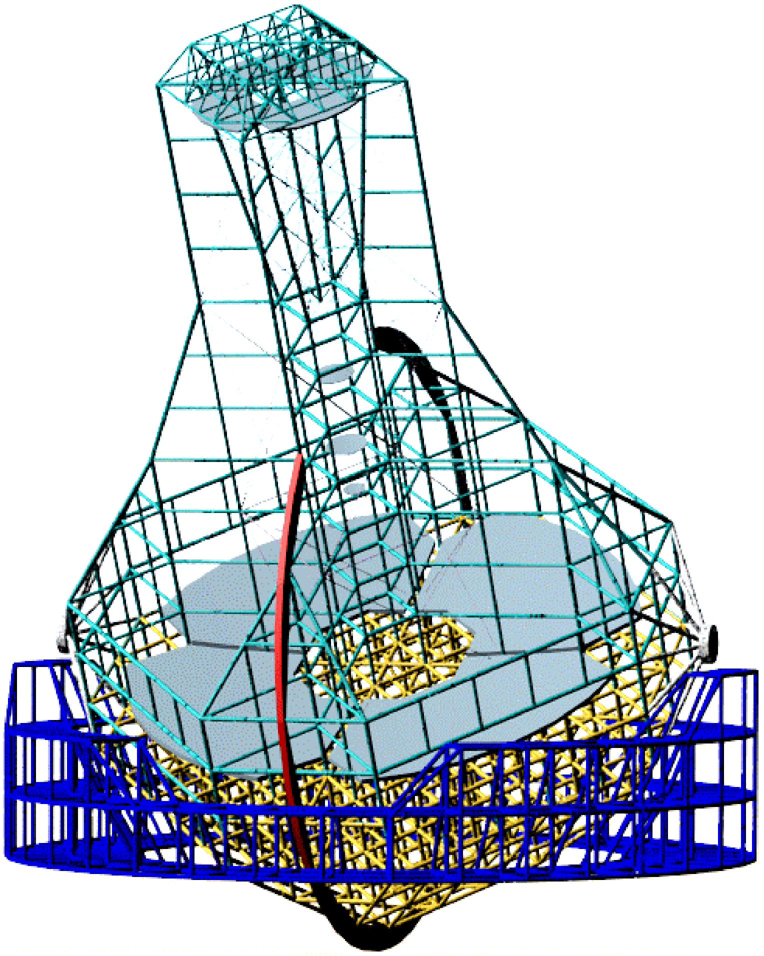

Figure 1. Baseline concept

Besides the most conventional solution in telescope design (traditional alt-azimuth mount) which are widely accepted and realised, this mechanical structure also introduces some innovative concepts, including:

- An azimuth ring instead of a conventional fork to minimise the distance between the tube and the ground. The azimuth ring is embedded into the ground, thus increasing the stiffness.
- An iso-static configuration is foreseen in parking position. Thus will the structure be allowed to expand freely during daytime.
- A hyper-static configuration is foreseen during operation. Thus the mechanical performance will reach an optimal stiffness during observation.
- Dust rejecting concept. Pollution of the optics is a major concern. Therefore the accumulation of dirt on the mechanical structure shall be minimised, rounding edges and corners and no flat surfaces. Thus the cleaning of the external surfaces will be facilitated.
- Dimensional instability due to residual stresses can be minimised with a running in period prior to the integration of the optical components. Alternate parking positions can minimise the asymmetrical creeping of the structure.

- Warm blood-cooling system. The necessity of an enclosure can be put in discussion if the mechanical structure has its own internal air-cooling system. This cooling system will increase the temperature change rate before observation. Also the energy consumption is minimised due to the small amount of volume to be cooled (e.g.: The volume of the tube structural element is equivalent to a 10-m class telescope enclosure). An important consideration for thermal control is to select a suitable surface coating on the structure to do three things: reduce solar absorption during the day time, minimise radiative cooling during the night time and reduce optical reflections on structural parts close to the optical beam.

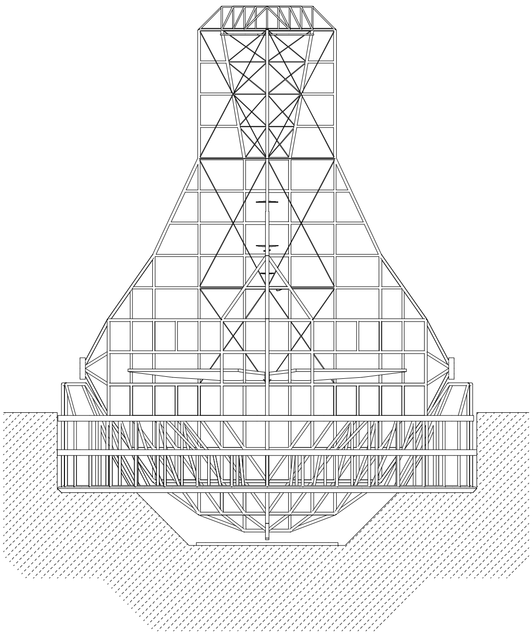

Figure 2. Front view, pointing at zenith.

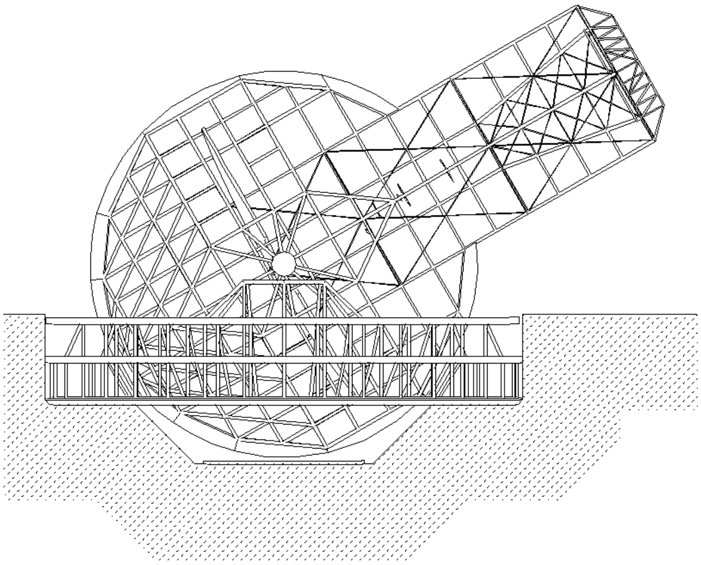

Figure 3. Side view, 60° zenithal distance.

- Local protection of the telescope critical parts (M1, M2 and corrective optics). In particular the M1 cover is divided in 4 sectors, which can be slid over the M1. One cover is also equipped with M1 handling unit and washing unit. Once the covers are all positioned over the M1, the telescope tube can rotate to reach the defined parking position.
- Modular design. A maximum of standardisation of parts and components has been adopted as well as the selection of commercially available components. This also will allow the fabrication of modules to be started well before all the aspects of the telescope will be finalised.
- Maximise the number of potential contractors. Adequate choice of materials and manufacturing processes will assure that a sufficient number of contractors will be able to supply components, thus avoiding monopoly situations with the related risk of unjustified increase in costs
- The size and mass of each element is minimised. This results in easier transport and more flexibility and redundancy during

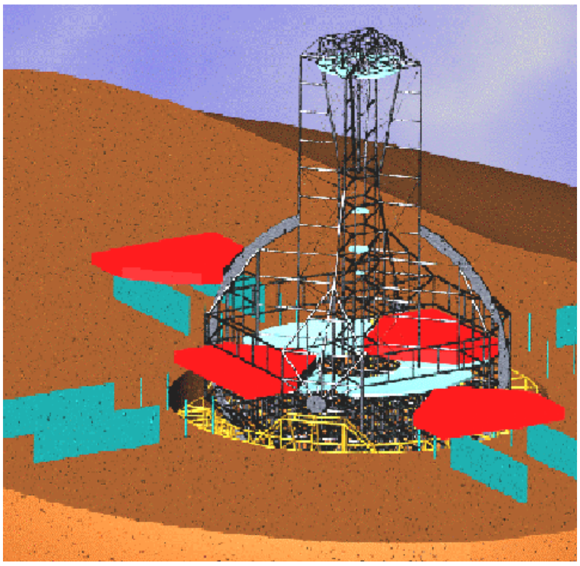

Figure 4. Mirror covers

installation (e.g.: several small cranes instead of one large crane, etc).

- Fabrication on site of part of the structural elements can also reduce the transport costs. Since this is related to manufacturing process typical of each manufacturing company, it cannot be introduced in to the design at this early stage
- Self-machining structure. The journal of the bearing will have the final machining on site, using the structure itself has a large-scale machine tool.
- Self-supporting structure. The structure is divided in floors, each floor serve as a stand for the next floor during assembly. This technique will minimise the amount of scaffoldings and the risk associated to the installation of large elements.

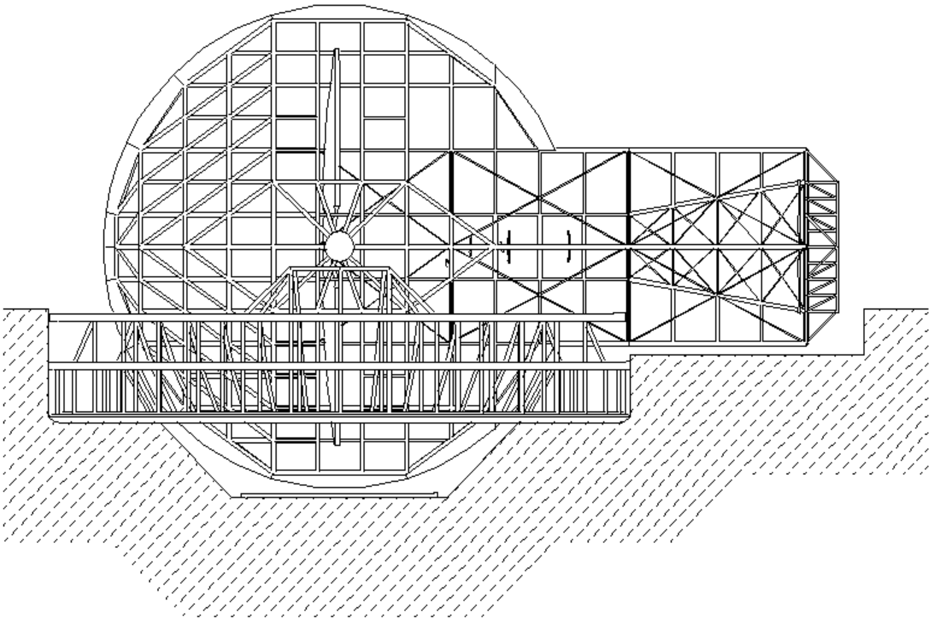

Figure 4. Parking configuration.

- Rotation range of ± 90° from zenith facilitates installation and maintenance of the secondary mirror optics.

Subsystem	Mass [tons]
Tube Structure.	**6500**
Primary mirror + cell. (Mirror area density 160 Kg / m$^{2)}$.	**2000**
Secondary Mirror + cell. (Mirror area density 100 Kg / m$^{2)}$.	**150**
Corrective optics + instrumentation.	**150**
Azimuth Ring Structure.	**8000**
Azimuth Track.	**5000**

Table 2. Baseline concept, mass breakdown.

4. Drives

In choosing the max. velocity and the acceleration to move OWL as $0.5^{o}.s^{-1}$ and $0.1^{o}.s^{-2}$ respectively, we have considered the following parameters:

- Slewing time: with such a large inertia we specified this to be about 3 minutes to cover the altitude range of 90• and about 12 minutes to make a complete revolution in azimuth).
- Induced centrifugal acceleration on the structure is of the order of 0.1g.
- Low dynamic range of tracking velocity to reach a good control. This is similar to the VLT, with maximum tracking velocity equal to the slewing velocity).
- Low blind angle at azimuth of about 1• , as with the VLT.

In the table 3 the estimated torque and power for both altitude and azimuth axes are summarised.

In case VLT like segmented motor would be used, and placed on the radius of 59m for both axes, for standardisation, the last row shows how many segments would be needed to produce the estimated torque.

	ALTITUDE	*AZIMUTH*
Inertia [Kg m^2]	2^{10}	5^{10}
Torque [MNm]	46	114
Power [kW]	400	1000
No. of VLT altitude motor segments (at 59 m radius)	177	438

Table 3. Baseline concept. Inertia, torque and power breakdown.

If the direct drives offer control torque without injecting friction, which is important for the control system performance, one has to consider that actually that performance depends on the ratio between friction and inertia.

It will be a future task to assess if, given the high inertia of OWL, rim-pinion drives or friction drives can be used without decreasing the performance of the telescope.

5. Performance of the mechanical structure

A preliminary investigation of the structural behaviour of the Rotating Support Structure has been carried out with various static and dynamic Finite Element Analyses (FEA). The FE Model displayed below represents the complete tube structure, which rotates about the altitude axis. Each of the mirrors M1, M2, M3 and M4 is represented by a distributed set of mass elements connected to the Tube structure. The structure is fixed to ground at the two bearings and the altitude motors along the longitudinal directions. The FE Model comprises about 4100 elements (beam, rod and mass elements). The global co-ordinate system of the Model assumes the x-axis identical to the Altitude axis, the z-axis pointing to zenith and the y-axis perpendicular to the x- and z-axes. Tube orientations different from Zenith are taken into account by rotating the structure about the altitude axis and adapting the boundary conditions of the Altitude motors accordingly. The analyses have been carried out with ANSYS.

Static Performance.

The results of the gravity load case are summarised in table 4. It shows the differential displacements and rotations between tube pointing to zenith and 60° from zenith. The maximum decentering value of 82 mm is obtained for M2. Due to the fact that in the present optical design M2 is a flat mirror, this motion does not have to be corrected. The maximum piston of about 21 mm occurs as well at the M2-Unit and the maximum tilt is obtained at the level of the M4-Unit with about 75 arc seconds.

A static wind load case for a typical wind configuration has also been analysed. The table 5 summarises the absolute displacements and rotations of the four mirror units for a mean wind speed of 10 m/s, tube pointing 30° from zenith and wind facing M1. In this case the following maximum static deflections without accounting for the gravity effects are obtained for the M2 Unit: 1 mm decentering, 0.2 mm piston and 1.7 arcsec tilt.

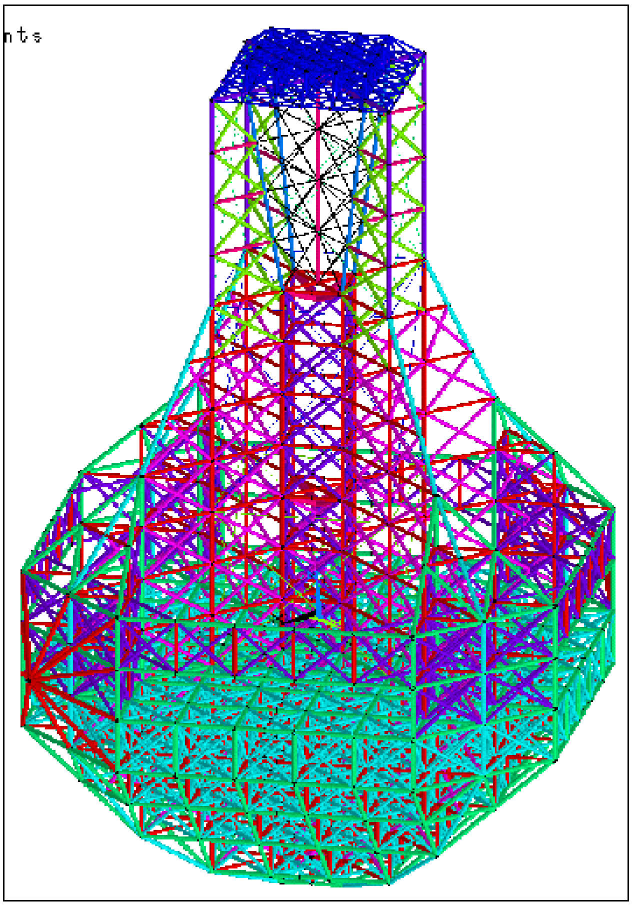

Figure 5. Finite Element model

Dynamic Performance.

Based on the FE model mentioned before, the dynamic performance of the structure has been investigated with a Modal Analysis and several Harmonic Response Analyses.

The results of the Modal Analysis are listed in the table 6 in terms of mode numbers, eigen frequencies, corresponding effective mass distribution and mode shape descriptions. In this configuration the motors are assumed to be locked and the tube is pointing to zenith. Except the first mode, only those modes are indicated in the table that might have an influence to the optical performance of the telescope structure.

Location	Displacement [mm]		Rotation [arcsec]
	Decentering	Piston	Tilt
M1	17.3	11.2	23.6
M2	*82.0*	20.6	65.5
M3	16.8	14.7	19.0
M4	32.3	17.8	74.8

Table 4. Gravity Loading (differential deflection between Zenith and 60° from Zenith)

Location	Displacement [mm]		Rotation [arcsec]
	Decentering	Piston	Tilt
M1	0.1	0.1	0.4
M2	1.0	0.2	1.7
M3	0.2	0.1	1.1
M4	0.6	0.2	1.6

Table 5. Static Wind Loading (absolute deflection for 10 m/s at 30° from Zenith)

Mode	Frequency [Hz]	Effective Mass [%]			Mode Shape
		X	Y	Z	
1	1.131	-	-	-	Top Tower, rotation z
2	1.354	-	8.1	-	Top Tower, lateral y
3	1.400	5.6	-	-	Top Tower, lateral x
5	1.748	-	6.1	-	Top Tower, lateral y
6	1.808	7.4	-	-	Top Tower, lateral x
9	2.429	10.9	-	-	Intermediate, lateral x
11	2.500	-	4.7	-	Intermediate, lateral y
13	2.849	11.9	-	-	Intermediate, lateral x
14	2.962	-	7.0	-	Intermediate, lateral y
17	3.208	0.9	-	-	Top Tower, lateral x
18	3.212	-	0.2	-	Top Tower, lateral y
20	3.289	17.5	-	-	Inter + Top, lateral x
22	3.396	-	33.0	-	Inter + Top, lateral y
24	3.560	-	-	89.3	All, vertical z
Cumulative Mass:		54.2	59.2	89.3	At mode 24 (3.56 Hz)
Cumulative Mass:		93.6	94.0	93.5	At mode 62 (6.13 Hz)
Cumulative Mass:		96.3	95.8	96.6	At mode 150 (12.7 Hz)

Table 6. Dynamic performance, Eigenfrequencies (locked rotor, Zenith, total Mass: 8744 tons)

The 1st mode at 1.1 Hz is a pure rotational mode about the vertical optical axis and does not influence the optical performance of the Telescope. The first important mode for the optical performance occurs at **1.35** Hz. As shown in the mode shape plot (figure 6), it represents the lateral shear mode of the Top Tower along the global y-axis. The 3rd mode at **1.4 Hz** is again a lateral shear mode along the global x-axis. Since the first eight modes are either rotational modes about the vertical z-axis or contain only a relatively small fraction of effective mass (only part of the top tower is affected by the vibration), their natural frequency can easily be increased by changing the design and/or using composite material only for the Top Tower part and/or using Silicon Carbide secondary mirrors. The first global mode of the structure occurs at **2.43 Hz**. In this case also the intermediate structure is affected by the vibration. The stiffness and compactness of the structure in vertical z-direction is confirmed by the fact, that only one mode at **3.6 Hz** contains almost 90 % of the total mass.

The influence of the motor torque to the lateral displacement of the M2 unit has also been simulated. In this case the tube is pointing to zenith and the rotor is free about the altitude axis. A harmonic unit load representing the motor torque has been applied to the structure. The transfer function (figure 7) shows the dynamic response displacement of the M2 unit along the global y-axis to the motor torque. The 1st peak is much less pronounced than the 2nd one. This confirms the assumption that the lowest mode involves only a small fraction of the total effective mass and can be cured quite easily.

Another method to improve the dynamic behaviour of the structure is to attach a dynamic vibration damper to the top unit. As illustrated in figure 8, a small mass is linked to the large effective telescope mass by a highly damped spring-damper hydraulic. The damper and the spring constant of this system can be optimised in such a way, that the amplitude of the large telescope mass for the lowest natural frequency is being significantly reduced compared to the configuration without a vibration damper. Most of the vibration energy of this mode will be absorbed from the vibration damper. The advantage of such a system is that it can be operated in active as well as in passive mode. In the latter case, no additional energy or control system is required.

Such dynamic vibration damper systems have been already successfully installed in high story buildings, in order to decrease significantly the high amplitudes during wind excitation and to save cost by avoiding additional design stiffening. A typical example is installed in the Citicorp Center in New York. The building height is about 280 m and the additional vibration damper mass is 370 tons which is only 0.5 % of the total building mass. The additional mass is horizontally fixed to the 63rd story by two hydraulic spring-dampers (figure 9).

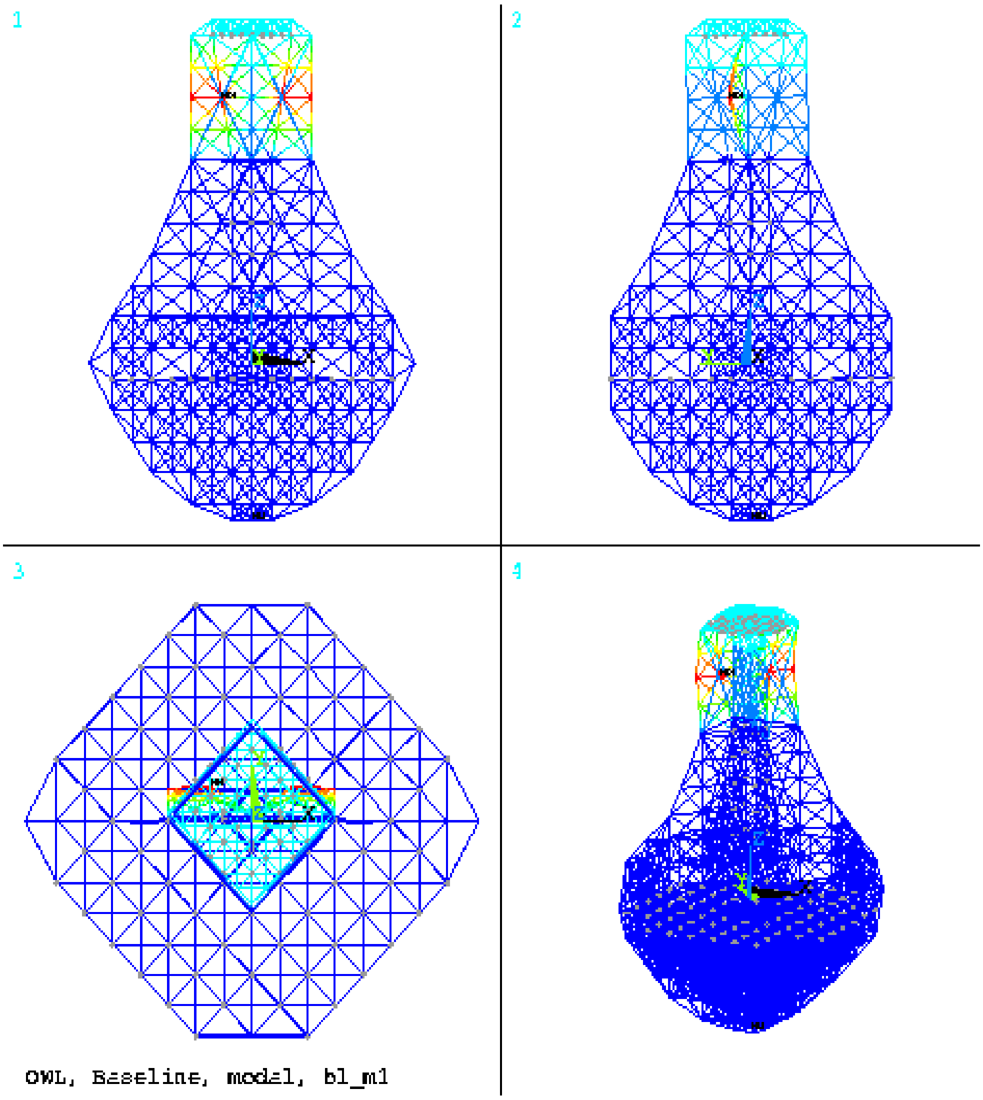

Figure 6. 2nd Mode Shape

A simulation with a vibration-damper system has been done with the telescope structure in order to demonstrate the improvement of the dynamic performance. The same wind load configuration as for the static wind load case described before has been applied dynamically for a frequency range between 0.5 and 10 Hz. The resulting transfer functions of the lateral displacement of the M2 Unit are shown in figure 10. The top curve represents the nominal case without a vibration damper system. The maximum deflection at the lowest resonance frequency is **51 mm**. If a vibration damper system of 10 tons (2 % of the effective modal mass) is attached to the Top Unit, the maximum amplitude can be significantly reduced by about 60 % to **20 mm**. This system might also become very useful under survival load conditions like strong wind and earthquake loads.

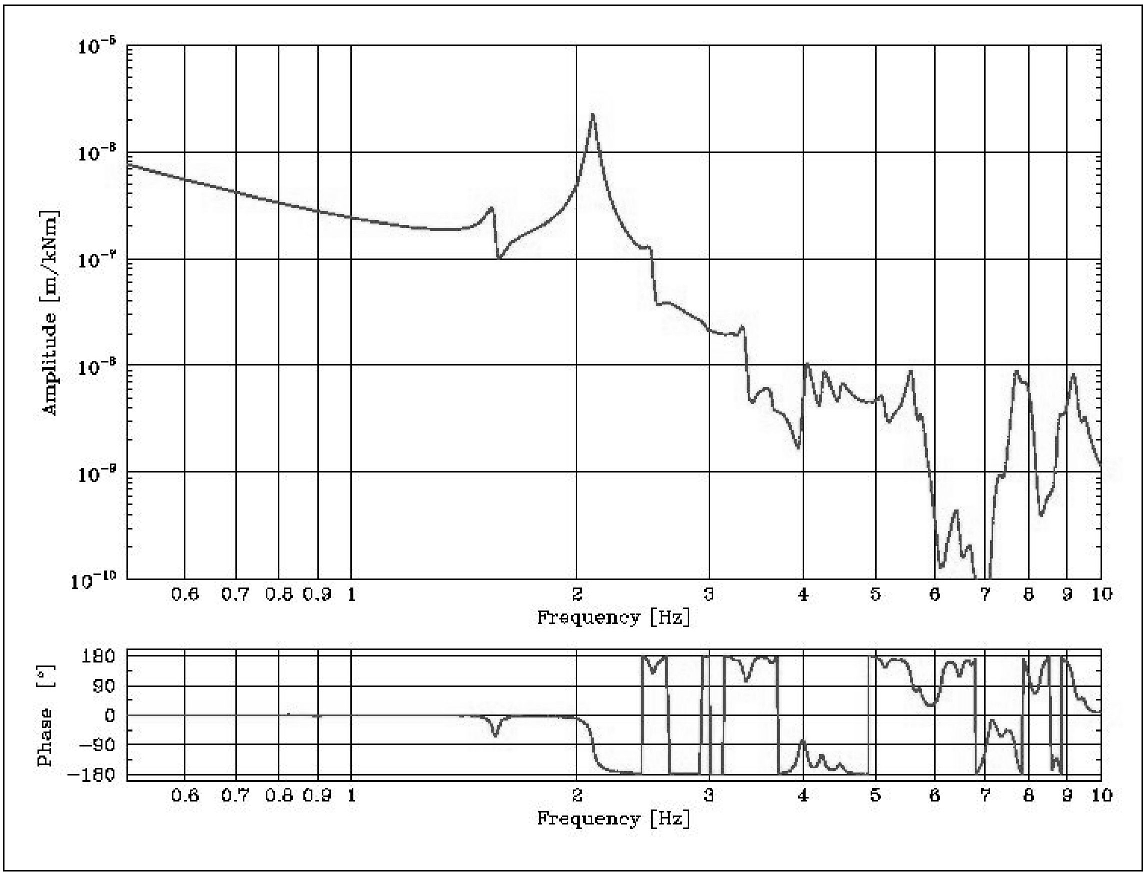

Figure 7. Transfer function M2 unit (Motor torque, free rotor).

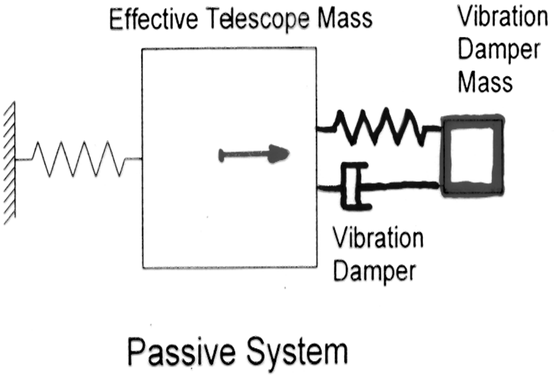

Figure 8. Dynamic vibration damper

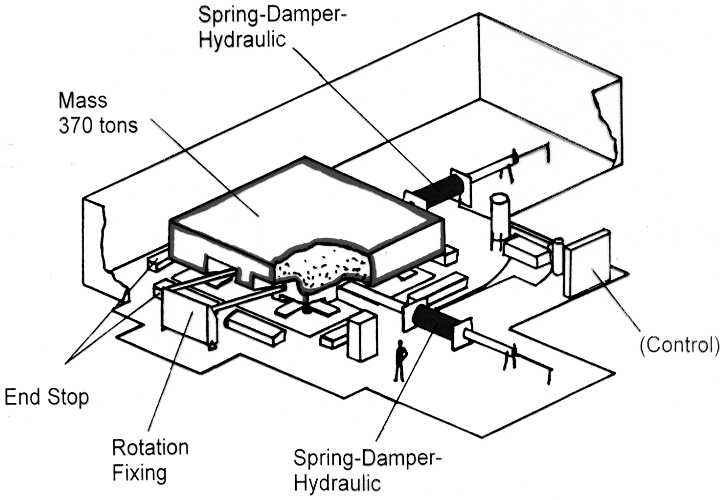

Figure 9 Example: Citicorp Center, New York. Height 279 m, additional Mass: 370 tons (0.5 % of building)

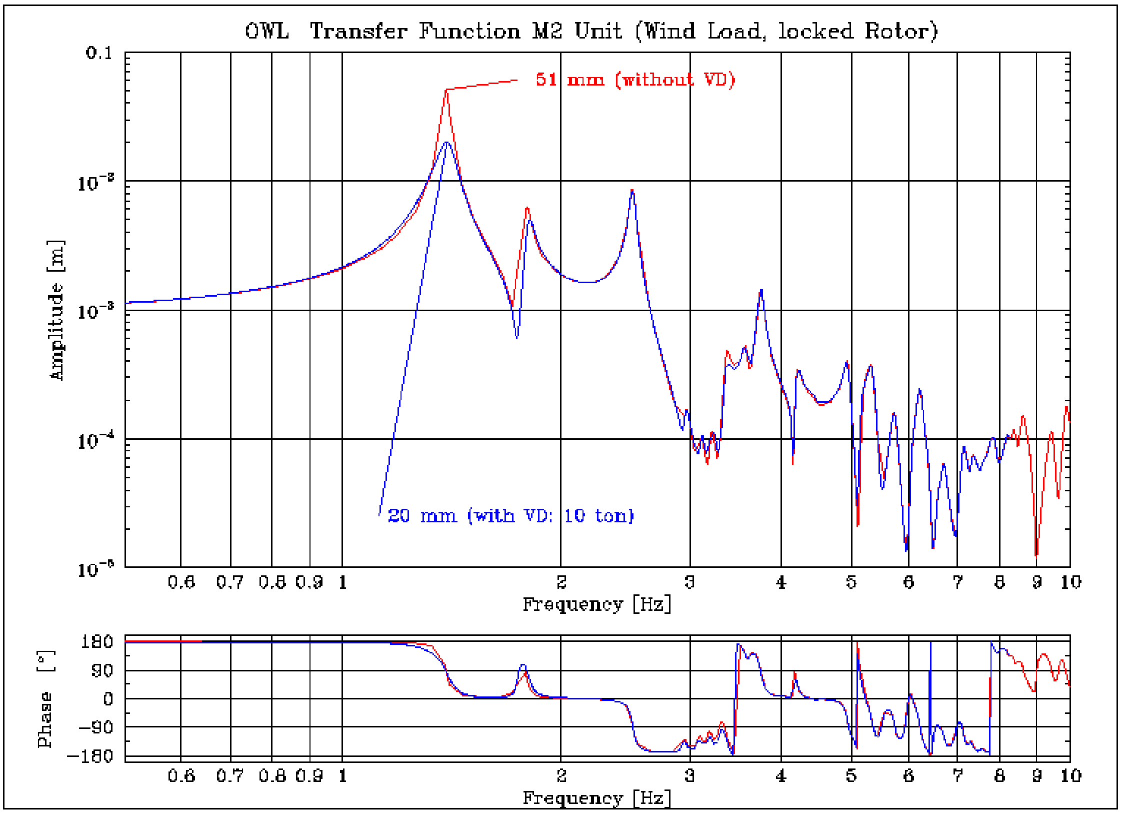

Figure 10. Transfer Function under wind load with and without Dynamic Vibration Damper System.

6. Alternative designs

Several other concepts have been also investigated. These alternative concepts have not yet reached the same degree of maturity as the baseline concept in terms of performance and feasibility. However these alternative concepts have the important role to validate once more the strategies and solutions adopted for the baseline concept.

Here below are some examples of alternative concepts.

Rocking chair concept.

This mechanical structure (figure 11) is associated to the so-called "OWL 4-mirrors optical design" [1]

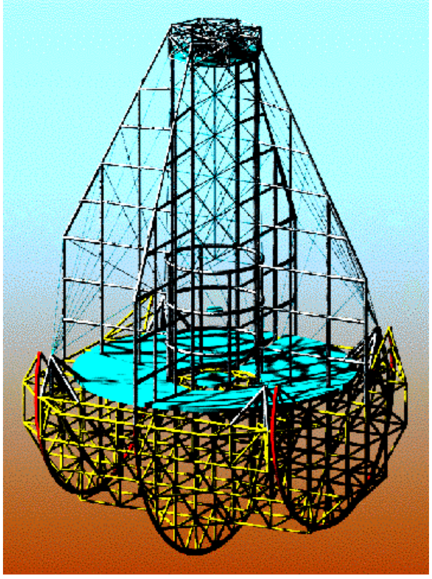

Figure 11. Rocking chair concept

Separating the secondary mirror from the M1/Corrector structure.

Investigating other possible concepts to build OWL, one has considered the possibility to mount the secondary mirror, turning around the altitude axis, on an independent arch structure, which can move around azimuth axis only, both movements being synchronised with the M1 (figure 12). This exercise has been developed with the aim to increase the telescope altitude axis controllability under wind disturbances, the altitude being most affected. In the classical concept the control bandwidth of the altitude axis will be defined by the "locked rotor" frequency which is represented in the baseline concept by the frequency of the M2 tower. In the case outlined here, the control bandwidth of the position of M2 will be defined by the secondary mirror structure mass and the stiffness of the motor mounting, which can be designed for relatively high values (eigen frequency in the order of 5Hz). To synchronise the motion between the two parts, commercial transponders can be used, which deliver positioning accuracy within some tenths of a millimetre. The power of the motors to control the motion of M2 structure it is estimated in about 30 kW, to move at 3 Hz by a range of about 50mm.

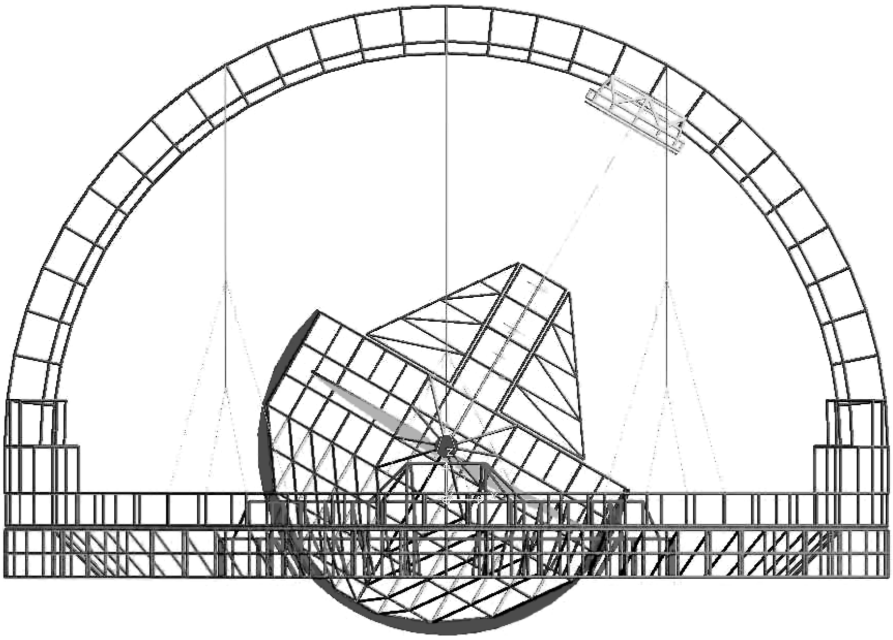

Figure 12. Arch concept

7. Conclusions

We can conclude that the rotating support structure of a 100-m optical system can be build as per today using conventional, well understood and largely realised technology. Moreover, the conservative approach of using optical element made of Zerodur in the performance analyses put OWL on the safe side. That means that we do not have to speculate on future development concerning lightweight optical materials. Also the choice of commercial available components is an indication that the mechanical structure will not represent a technological risk in the OWL project and the foreseen budget can be respected.

8. References

[1] P. Dierickx, J. Beletic, B. Delabre, M. Ferrari, R. Gilmozzi, N. Hubin, *The optics of the owl 100-m adaptive telescope*, this conference.