ADAPTIVE STRUCTURES AND MECHATRONIC COMPONENTS FOR VIBRATION AND SHAPE CONTROL OF SATELLITE PRECISION PAYLOADS

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Abstract

Smart materials and actuators for in-orbit jitter and shape control for precision instruments are discussed together with effects of very low temperatures and eventual nonlinearities. Simulation and lab model demonstration results together with different types of actuators are given for solar array and precision optical bank active vibration attenuation as well as for reflector shape control. The latter calls for circumferentially and radially arranged actuators.

1. Introduction

Major elements of in-orbit requirements for mechanical systems of satellites such as telescopes and precision instruments are related to very low distortions under thermal and dynamic excitations. This is met by proper design concepts and material selection such as CFRP with very low coefficients of expansion. Such „passive" approaches come to their limits for ever increasing requirements with distortion allowables of fractions of micro-meters or milli-arcseconds of pointing accuracy. Then active shape control and damping techniques come into play, where negative effects of disturbances are to be reduced or counterbalanced by (integrated) actuators which are triggered by appropriate controls. Potential applications become obvious from figure 1.1.

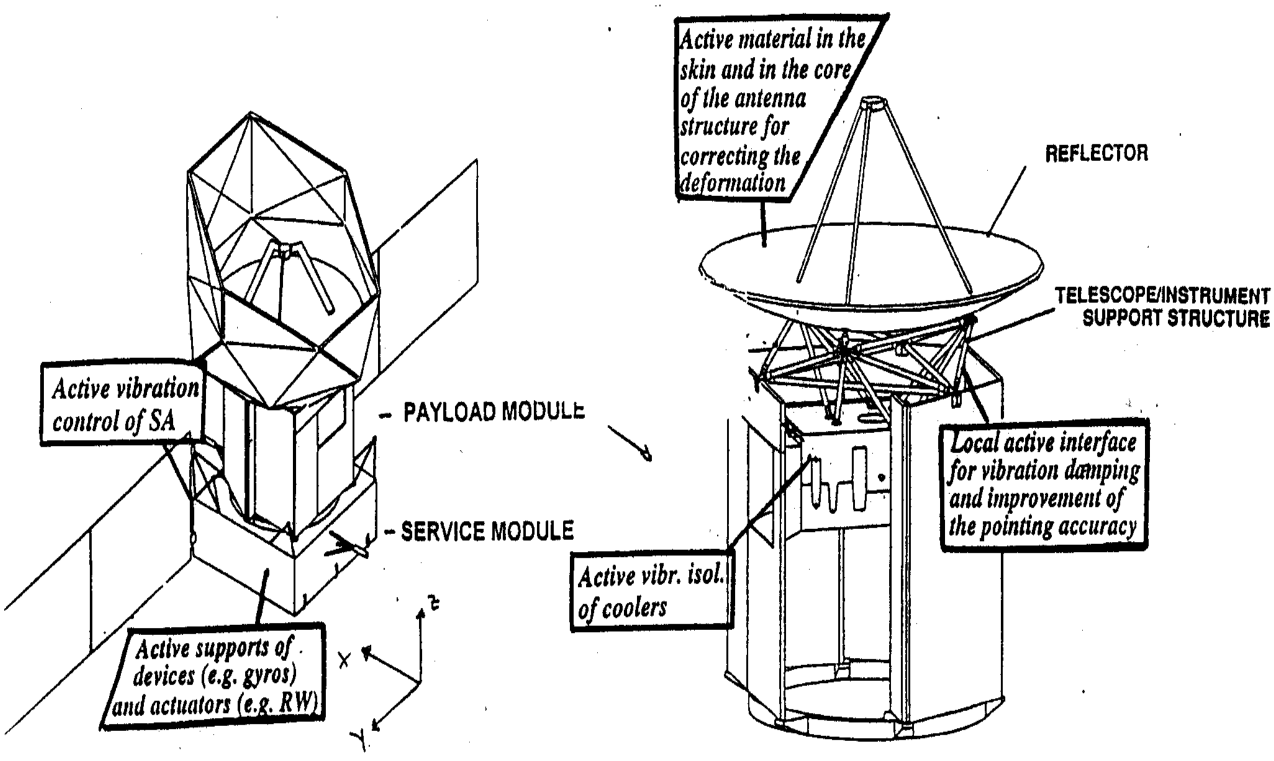

Fig. 1.1.: Application Scenario

While such concepts have found considerable interest in research, applications in space are still quite limited. One major reason for this is that actuators and their properties often have not been sufficiently addressed. Benefits for precision instruments can be realised only by an integrated consideration of actuators together with their performance, positioning, mass, volume and power to be optimized. This will be the focus of this paper. Different and typically relevant types of actuators, positioning and control strategies will be discussed together with potential applications for precision payload platforms, large solar arrays and reflectors.

2. Relevant smart materials and actuator types

Relevant actuators in principle are a series „configuration“ of power amplifiers together with electrical-mechanical power transfer mechanisms. For the latter, most often an arrangement of piezoceramic materials (especially PZT) is used. Of course mass and volume of amplifiers have to be considered in design. Power requirements are quite small due to the usually very small strokes involved in high precision systems.

In such actuators enforced strains are often generated via piezoelectric materials by applied electrical fields according to

$$e_p = d_p \text{ x } \Delta E$$

where e_p is induced (piezo-)strain, d_p an ‘effective’ (since non isotropic) coefficient of expansion and ΔE the applied electrical field. Depending on the type of application, these materials are used in different actuator configurations such as

- linear actuators, where a stack of piezoceramics (PZT) is used to achieve linear actuation strokes typically in the sub-mm range. Industrial types of actuators are quite matured, but may be relatively heavy.
- PZT plates (planar actuation); also quite matured, but planar actuation strains might be undesirable in some cases
- Piezo-fibres with thicknesses in the range of some μm up to sub-mm. Electrical contacting and intergation of fibres in materials and components is one of the challenging tasks.
- Combinations and special forms such as proof mass actuators (PMA), where inertia forces generated by (small) masses accelerated e.g. by linear actuators are used as actuating lateral forces.

While from all types of such actuators commercial versions are available, they often have to be adapted to the specific area of space application. This is discussed in more detailed in the application chapter 5.

Typical properties of these smart materials are given in table 2.1.

Generally speaking, piezoelectric (mostly ceramic) materials do have high dynamic bandwith, but only relatively low strain and force levels can be generated. Coefficients of thermal expansion (CTEs) are low but

	piezo-ceramic (PZT)	piezo polymer (PVDF)	electro-strictive (PMN)	magneto-strictive (Terfenol D)	SMA (Nitinol)
Planar Max Strain	0.13%	0.07%	0.1%	0.2%	2%-8%
Modulus (GPa)	60.6	2	64.5	29.7	28-90
Density (kg/m3)	7500	1780	7800	9250	7100
Energy Density (J/kg)	6.8	0.28	4.1	6.4	250-4000
Hysteresis	10%	$> 10\%$	$< 1\%$	2%	High
Temp Range (°C)	-20 to 120	Low	0 to 40	High	-
Bandwidth	100 kHz	100 kHz	100 kHz	< 10 kHz	< 5 Hz

Table 2.1.: Essential smart material data

exceed those of very high precision structural materials. This can be at least partly compensated by proper combination with base materials having negative CTEs.

Transfer ratios from electrical to mechanical power is quite efficient and is easily exceeding 50 %. Play or slip stick is negligable, and most often lever of „gear“ systems for stroke amplification can be avoided.

Temperature dependency of Piezo properties

Many space applications are in cold if not cryogenic environment. While reduction of CTEs can be observed at levels below – 50 ° C and in many cases is beneficial, the possibly significant reduction of piezoelectric coefficient of expansion as outlined in figure 2.1. has to be taken into account in cryogenic applications.

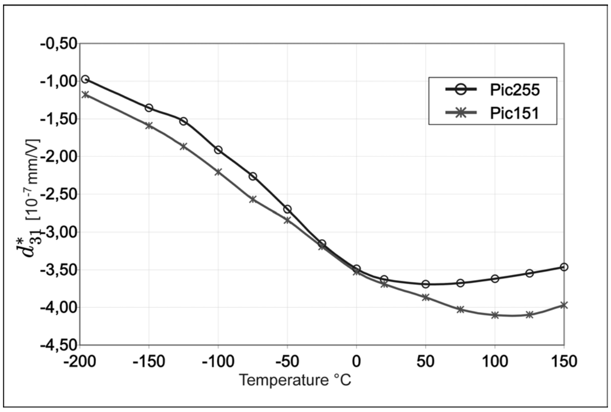

Fig. 2.1.: Temperature variation of Piezo strain

Material nonlinearity

When it comes to details, a non-linear behaviour of relationship of strain vs applied electric field has to be observed. Though practical consequences of this are small if sufficient stroke and power is available. This can lead to slightly smaller efficiency or slightly increased power consumption. Possibilities to compensate such nonlinearities are the use of different actuator control techniques which linearize the output vs. given input variations.

3. Positioning of actuators

Since the required control goals are to be achieved with the smallest number of actuators possible, proper positioning within the system to be controlled is important. While in some cases such positions are immediately obvious or given by other constraints, some physical criteria can support this selection. Basically, the actuators should be positioned at places of relatively high energy content compared to other positions. For strain inducing actuators this usually means areas of relatively high (modal) strain energy. For PMAs, which can be considered as kind of vibration absorbers, this are areas of relatively high kinetic energy. This basic principle of these considerations also become clear from figure 3.1.

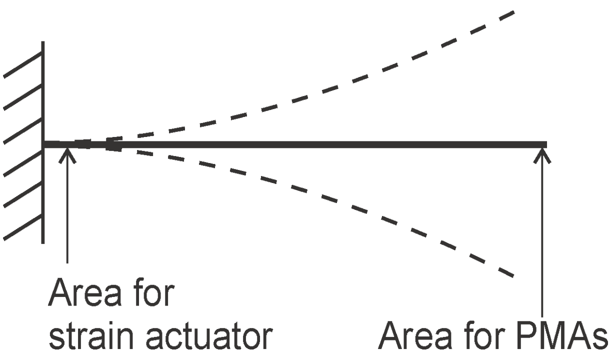

Fig. 3.1.: Basic rules for actuator positioning

Quantitatively and still more strictly this can be evaluated for example by using the product of balanced gains g_i and Hankel singular values γ_i which gives a measure of controllability and observeability of eigenmodes number i to be controlled:

$$g_i \gamma_i = \frac{b_i b_i^T (u_i^T v_i + w_i^2 v^T v)}{4 \delta_i w_i^{\ 3}}$$

with b_i, u_i and v_i being participation factors and displacement and velocity output vectors, respectively, while δ_i and w_i are modal damping and eigenfrequency. Such criteria then can be part of an overall design optimisation task.

4. Actuator types and control laws

The overall control architecture can be differed between high authority control (HAC) and low authority control (LAC). Loosely speaking, in HAC relevant response data are measured at some points, while actuation is triggered at different other points. In addition, mathematical observer models which allow the estimation of the full system state from the usually small number of measured values are to be used. In LAC, data are measured at the actuator positions and more or less directly fed back to the actuators via different control laws. While HAC often may lead to better overall performance than LAC, it is much more complex and requires also certain provisions to keep the control loop stable. LAC is easier to implement, and control loop stability can be easier achieved. Most prominent examples of LACs are:

- direct velocity feedback (DVF), where the output of a velocity sensor is directly fed back to the actuator, multiplied by a gain factor
- acceleration, position and force feedback, where these data are measured and fed back via additional filters, i.e. with additional dynamics within the feedback loop.

An overview and short evaluation is given in table 4.1

Control method	Direct Velocity Feedback (DVF) [7]	Positive Position Feedback (PPF) [8]	Acceleration Feedback (AF) [9]	Integral Force Feedback (IFF) [10]
Feedback signal	velocity	displacement	acceleration	strut force
Controller type	P	PT_2	PT_2	I
Design parameters	gain	gain, frequency and damping of filter	gain, frequency and damping of filter	gain
Stability	for positive gain (no actuator / sensor dynamics !)	within parameter bounds	for positive gain	for positive gain
Influence on selected modes	not possible	possible by tuning of filter frequency	difficult	not possible

Table 4.1.: Different local authority controllers

5. Applications and lab model demonstrations

In this chapter some potential applications in satellites are discussed. Again, special emphasis will be given to the different types of applicable actuators.

5.1. Solar arrays: Active damping and S/C interface force minimisation

The damping of large solar arrays has two major interests:

- avoidance of disturbance rejection on the satellite platform

A large solar array usually has low frequencies (typically lower than 0,1 Hz) and very low damping rates. Due for example to AOCS action or thermal shocks, the solar array then vibrates for a long time period. This motion together with inertia forces is transmitted to the satellite, which can be harmful for high accuracy payloads.

- simplification of the attitude control system

The AOCS is usually designed in such a way that the solar arrays cannot be excited in their eigenfrequency range. This superimposes constraints on the period length between two successive AOCS actions. The provision of a high damping of the solar array allows release of this constraint and consequently also leads to a saving of fuel consumption. Moreover the requirements to the structural dynamics properties of the solar arrays may be reduced.

Fig. 5.1. Active Vibration attenuation for a solar array interface farce to the bus S/C

Active material embedded in the solar array could be applied to the damping of large solar array vibrations. However this solution demands a rather complex development specific of each type of solar array. A simpler and more direct solution is the implementation of an active interface that can directly be connected to the solar array pointing drive, or the solar array's yoke.

Figure 5.1 shows the principle of such an interface for damping the low frequency bending modal shapes of large solar arrays in conventional configuration: the active interface is directly attached to the solar array pointing drive or another typical interface. The benefit of such an active interface is outlined in figure : force (disturbance) amplitudes to the S/C become smaller and are damped out in significant shorter time period.

5.2. Mirror support truss: active damping and pointing control

In figure 5.2 a lab model set up for interferometric telescopes is shown which has been investigated at Astrium Friedrichshafen [3].

Special struts for passive and active damping have been designed to replace nominal struts at selected positions. The active struts include piezoelectric stack actuators (PI P-845.60) mounted with a flex pivot to avoid damage by bending moments as well as quartz force sensors (Kistler 9321B). The sensor charge signals are amplified (Kistler 5011B) and sampled. A digital controller is realised in real-time on a digital signal processor (DSP) to compute the control law.

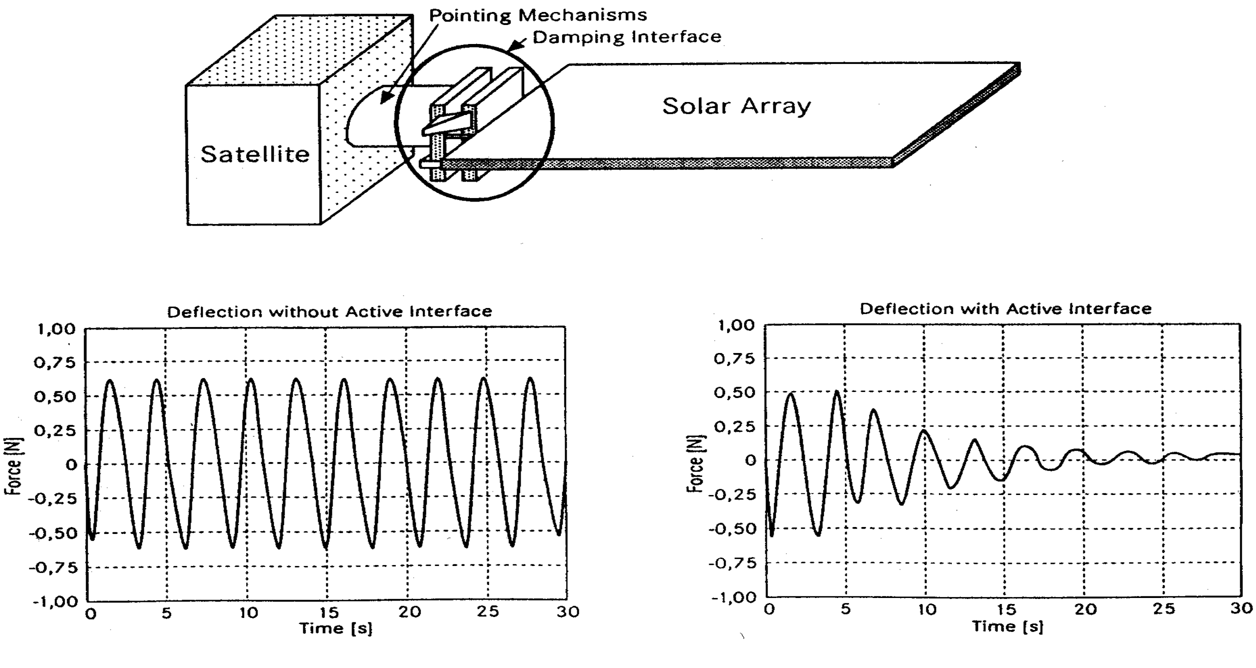

Fig. 5.1.: Active vibration attenuation for solar array interface force to the S/C bus

The resulting control inputs are D/A converted and fed to a power amplifier (PI E-505.00) to drive the piezoactuators. The A/D and D/A converters as well as the DSP are controlled with a Pentium PC using the MATLAB /Simulink Realtime Workshop and the software TRACE and COCKPIT by dSPACE. This combined hardware / software solution allows to quickly change parameters or types of control laws using MATLAB /Simulink dynamic models which are down-loaded to the DSP. A typical frequency response function (FRF) of uncontrolled vs. controlled system (3 active struts) is given in figure 5.3.

Similar applications can be in the vibration and pointing control of (secondary) mirror support trusses. In that case, trade off has to be carried out between structurally integrated actuation and those executed via eventual secondary mirror pointing mechanisms.

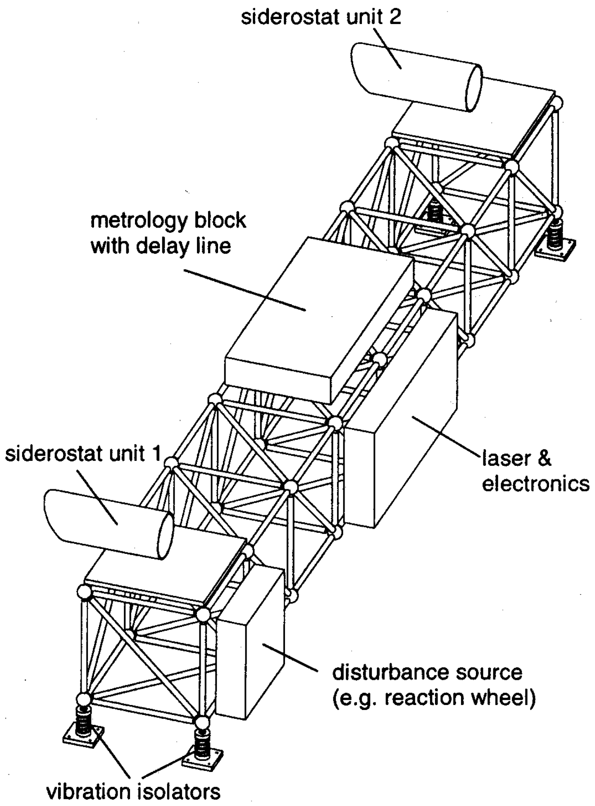

Fig. 5.2.: OISI testbench (Astrium FN)

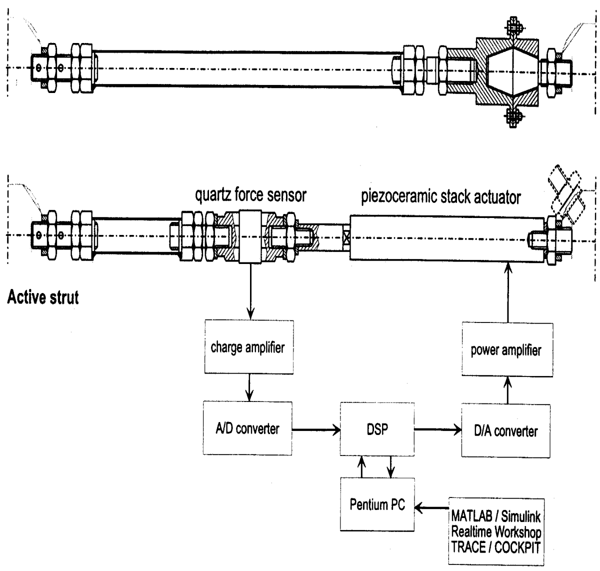

Fig. 5.3.: Active struts

5.3. High precision mirror platform: vibration attenuation via proof mass actuators (PMA)

PMAs can be considered either as kind of lateral shear force provider or as active vibration absorbers. They are specifically apt for vibration attenuation in precision platforms or optical banks.

PMAs for jitter control should have relatively low resonance frequencies in the order of 10 Hz or lower, while commercially available actuators usually are very stiff with resonance frequencies typically in the 200 Hz range and above. This necessitates some specific development, as outlined in figure 5.4. and realized in prototype hardware models. The low stiffness of these special PMAs would require special precautions for launch load sustainability. In order to avoid costly launch locks, investigations are currently under way to provide adaptive stiffnesses (high stiffness at launch, low stiffness in orbit). Mechanical means via nonlinear springs and „electrical“ means by provision of proper filters in the control loop are treated against each other.

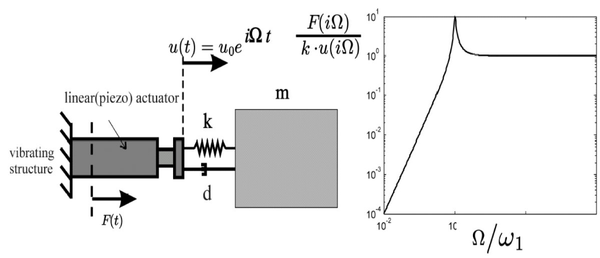

Fig. 5.4.: Proof mass actuator (PMA)

5.4. Thermo-elastic shape control of precision reflectors

An optimal reflector design and shape control problem means the determination of structural parameters (geometry, face sheet lay-up etc.) and control parameters (actuator positioning, size and geometry of piezo actuator layers, gain factors etc.) such that a light weight reflector has sufficiently controllable high shape accuracy under relevant load cases. Further structural and control requirements (e.g. actuator force amplitudes) are usually to be satisfied.

For treatment of this structure-control design problem a heuristic and nested decomposition strategy is used: first a reasonable if not optimal structural design is determined, and then actuator positions as well as control forces or voltages to be applied to the actuator are determined to minimise the total shape error generated under disturbance and control forces.

Investigations carried out with PZT patches used as actuators on the reflector´s rear side showed some benefit but also an inherent disadvantage of such plate actuators: piezoelectric or elastic coupling effects (e.g., Poisson´s factor) also cause forced (control) strains in other directions orthogonal to those desirable. So a decoupling into radial and circumferential actuation is desirable. This can be achieved for example by using radially or circumferentially integrated Piezo fibres, orthogonally arranged linear actuators, or orthogonally arranged backside „stiffeners“ with integrated actuating materials. A simulation result of such considerations is shown in figure 5.5 , where 40 actuators were „homogeneously“ applied to a reflector´s backside structure. Radially and circumferentially decoupled actuating forces show an improved rms error by a factor of 4 compared to that of the directionally coupled case e.g. when using Piezo plates.

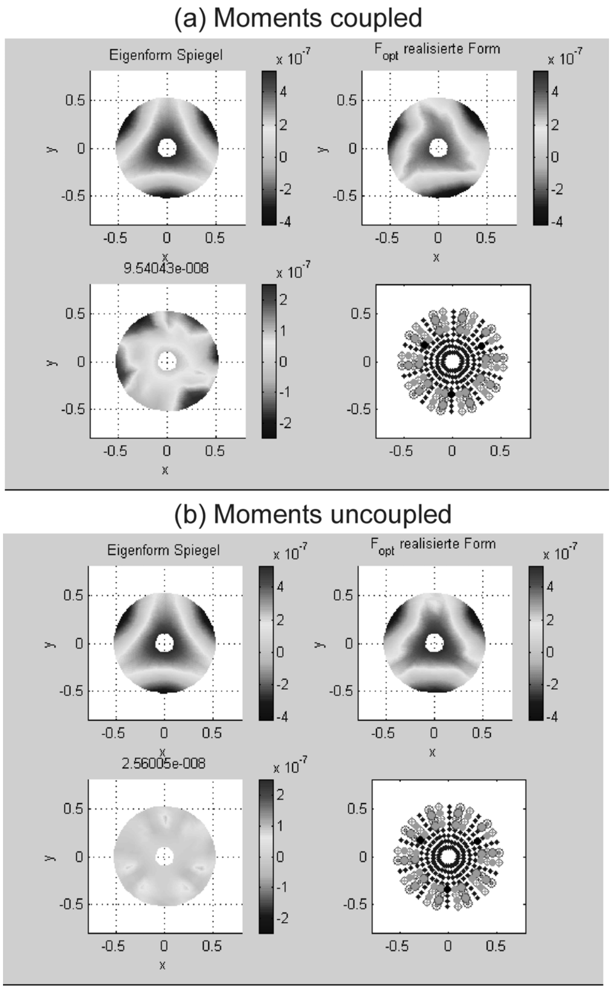

Fig. 5.5.: Shape control with planar (rms = 9.5E-8) and radial / circumferential (rms = 2.5 E-8) actuators

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