Dynamic error budgeting for performance analysis and optimization of active aerostatic bearings

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Abstract

Mechatronics in precision engineering has allowed for extended functionalities and improved performances but on the expense of higher design complexity and more error sources. Optimal design of precision mechatronic devices requires the use of tools adapted from precision and control engineering communities. Dynamic Error Budgeting can meet these requirements, combining and extending classical error budgeting and control design and analysis based on Bode diagrams.

Active aerostatic thrust bearings are a good example of the new opportunities and challenges brought by mechatronics into precision engineering. The performance of such bearings has been analysed experimentally, and the results presented here demonstrate the potential of dynamic error budgeting and active aerostatic bearings for precision mechatronics.

1 Dynamic Error Budgeting for precision mechatronic systems

The ever-increasing precision requirements in positioning and guiding systems have led to the development of design tools for predicting and analysing their performance. Error budgeting is a classical approach in precision engineering for allocating the allowed error within all the components of the system. Dynamic Error Budgeting [1] (DEB) has been proposed for precision mechatronic systems, where the influence of the frequency-dependent disturbances acting on a closed loop system needs to be analysed too. DEB allows the designer to assess the influence of each of the components of the active system and improve the performance over cost ratio by reducing development times. It can also be used on an existing system in order to find the limiting factor where improvement efforts should be focused.

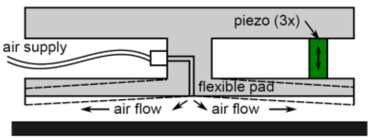
In DEB, the disturbances can be modelled as stationary stochastic signals, and their propagation through the control loop is analysed in a systematic way by using their

Power Spectral Density (PSD), and the systems plants are represented by their Frequency Response Function (FRF). The validity of the method relies thus on how accurately these PSD and FRF fit the reality. Modelling and identification are discussed in detail in [1].

The outcome of the DEB is the Cumulative Amplitude Spectra (CAS) of the total error of the system, and the contribution of each of the disturbances (see Fig. 4a). The end value of the CAS is the total error, and this value can be easily used to visually assess and optimize the performance of the active system (see Fig. 4b).

2 Application to active aerostatic bearings

Aerostatic bearings enable highest precision and resolution motion, but at the expense of relatively lower stiffness and damping compared to contact or hydrostatic bearings. Active control comes as a solution to overcome these intrinsic limitations and extend their functionality by adding short stroke positioning capability, normal to the bearing surface, by means of piezoelectric actuators embedded in the bearing [2] (see Fig. 1).



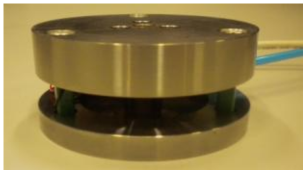


Fig. 1. Active aerostatic bearing (a) sketch and working principle (b) prototype

The performance of the active air bearings (stiffness, positioning resolution, bandwidth) is affected by a number of factors of different nature, e.g. the design of the active air bearing itself, broadband disturbances such as the electronic noise in the sensors and actuators, digital data processing, oscillations in feeding pressure, vibrations coming from the ground, etc. The achievable resolution is in the nanometre range, and any of these disturbances can be the factor limiting the performance. The design and performance of such systems can be thus analysed by DEB.

3 Active control strategy

The closed loop system considered for the control of active bearings is represented in Fig. 2. K is the controller, FF is the feedforward plant, P is the active bearing (displacement to voltage) and P_d is the disturbance plant, r is the tracking reference, *sn* is the sensor noise, *f* the external force, *fl* is related to floor vibration and *ac* is the actuator noise. The real error *e* and the measured error e_m are calculated as follows:

$$\begin{aligned} e = r - y = S((I-FF)r - Pac - fl - P_d f) + (I+S)sn \\ e_m = e - sn = S((I-FF)r - Pac - fl - P_d f - sn) \end{aligned} \quad (1)$$

where $S=(I-PK)^{-1}$ is the control sensitivity function.

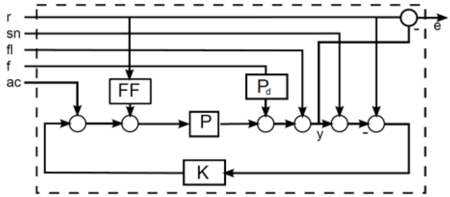


Fig. 2. Closed loop control system with main disturbances

All the elements of the system need to be modelled, based on either experiments, catalogues or theoretical model. Experimental and catalogue data has been combined here. For illustration, the FRF of the system plant *P* and the PSD of external force signal *f* (see Section 4) sent to the shaker are shown in Fig. 3.

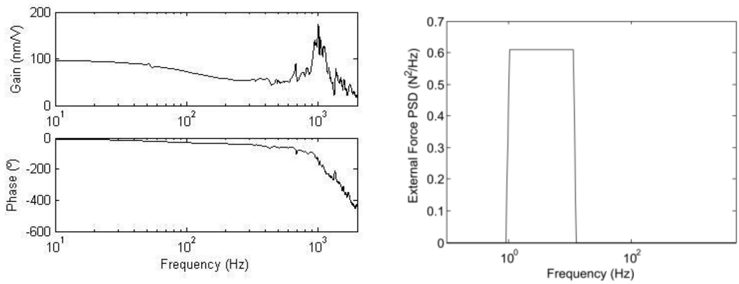


Fig. 3. (a) FRF of active bearing plant *P* (b) PSD of applied external force *f*

The controller has been synthesized by H_∞ mixed sensitivity optimization, which calculates the controller shaping the sensitivity function according to a performance weight $\omega_p(s)$ that focuses the optimization effort below a certain expected control bandwidth, defined by ω_B.

$$\|\omega_P S\|_\infty < 1, \quad \omega_P = \frac{(s/M^{1/2}+\omega_B)^2}{(s+\omega_B A^{1/2})^2} \quad (2)$$

4 Experimental performance analysis

The DEB and active control method proposed here has been tested experimentally on a setup that allows static and dynamic characterisation of active aerostatic thrust bearings. An external force of 1 N rms, distributed between 1 and 10 Hz (see Fig. 3b), has been applied with an electrodynamic shaker, and the resulting vibration level with controllers of different bandwidths has been tested.

In Fig. 4a, the CAS of the different disturbances has been simulated using DEB, for a controller with ω_B=1000 rad/s, being the external force the dominant disturbance, followed by the sensor noise.

Fig. 4b shows the measured and DEB simulated vibration level for different controllers, showing good agreement. A high bandwidth controller almost fully eliminates the effect of the external force applied by the shaker.

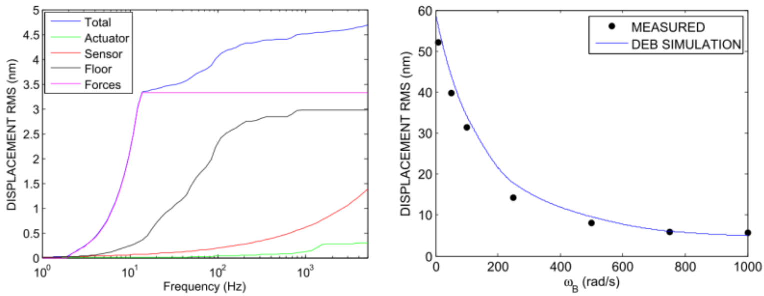


Fig. 4. a) CAS for ω_B=1000 rad/s b) Total error for different controllers

5 Conclusions

The experimental results presented in this paper demonstrate the high performance that can be achieved by active air bearings, in this case keeping the vibration level in a few nanometres even in presence of relevant external forces.

The results have been analysed by DEB method, which has proven itself as a useful tool for assessing the performance of high precision mechatronic systems.

References:

[1] L. Jabben, "Mechatronic design of a magnetically suspended rotating platform", PhD thesis, TU Delft, 2007.

[2] G. Aguirre et al., "A multiphysics model for optimizing the design of active aerostatic thrust bearings", Precision Engineering, vol. 34 (3), 2010, pp. 507-515.