New Folder Name Conceptual Design

CONCEPTUAL DESIGN OF ADVANCED LIGO VIBRATION ISOLATION SYSTEMS AND EFFECT ON VACUUM EQUIPMENT DESIGN

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I. INTRODUCTION AND PURPOSE

i. Develop a conceptual design for advanced LIGO detector vibration isolation systems based on current University of Western Australia Isolators [1] (see Figure 1).

ii. Determine any changes needed for LIGO vacuum chamber design to accommodate such advanced detector isolation systems.

II. DESIGN GOALS, ASSUMPTIONS AND REQUIREMENTS

i. Interferometer Design Goal for Seismic Noise Contribution

   A. Strain sensitivity of $h = 5 \times 10^{-23}/\sqrt{Hz}$ at 10 Hz [2]. This goal is for advanced detectors and corresponds to $x = 2 \times 10^{-19} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}$ at 10 Hz.

ii. Assumption on ground noise spectrum

   A. Ground spectrum at 10 Hz is $x = 10^{-9} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}$ and rolls off as f^{-2}.

iii. Assumption on isolation achievable (not including final pendulum stage)

   A. Horizontal isolation for multiple stage pendulum isolator

      a. Each pendulum stage has a natural frequency of f_o=1 Hz.

      b. The corner frequency is the frequency where the attenuation transfer function of a multiple stage pendulum starts rolling off as f^{-2N}, where N is the number of stages of the isolator (e.g. $\approx$ 5 Hz for a 6 stage pendulum)

      c. Above the corner frequency, the attenuation transfer function is $\approx N! \times \left(\frac{f_o}{f}\right)^{2N}$, therefore Horizontal attenuation at 10 Hz is $N! \times 10^{-2N}$.

   B. Vertical isolation

      a. Coupling factor to horizontal motion is .001*

      b. To achieve the strain sensitivity requirements in II.i, requires an attenuation of at least 10^{-7} at 10 Hz. The following vertical isolation parameters achieve this level of attenuation at 10 Hz: 4 stages with each stage having a natural frequency of 1.3 Hz, 5 stages with each stage having a natural frequency of 2 Hz, or 6 stages with each stage having a natural frequency of 2.6 Hz.

* Coupling factor taken from LIGO ICD Handbook, Version 2, October 23, 1992.

iv. Assumptions on maximum load of isolator and test mass for advanced detectors

A. Maximum mass of test mass is 200 Kg.

B. Maximum mass of six stage isolator, not including test mass, could be up to 1000 kg.

v. Assumption on maximum diameter of test mass

A. 20" diameter

vi. **Requirement on vertical stack attenuation derived from previous assumptions and design goal:**

A. **Attenuation of at least 10^{-7} at 10 Hz.**

vii. **Requirement on horizontal stack attenuation derived from previous assumptions and design goal:**

A. **Attenuation of at least 10^{-10} at 10 Hz.**

III. CONCEPTUAL DESIGN

i. DESIGN 1: 6 STAGE ISOLATOR

A. Isolator Element Design

a. Configuration

- The configuration of a single isolator element is shown in Figure 2. The springs of the top stage are triple straight cantilever springs. The springs are tapered to the ends such that they will have approximately uniform stress across the spring. The other stages will have curved springs. The curved spring design allows a maximum length for the spring in a compact form to allow lower natural frequencies to be achieved. An advantage of this curved spring configuration is that it allows the suspension point of the spring to be near to the centre of mass of the isolation stage.

b. Lowering resonant frequency of element

- To make the resonant frequency of each stage lower, the key point is to reduce the mass ratio m_{t_i}/m_i where m_i is the mass of the i'th individual stage and m_{t_i} is the total mass that the i'th spring supports. This is limited by total load of the isolator stack (i.e. < 1000 kg). Secondly, making the length of the arm of the cantilever spring longer will reduce the resonant frequency. This is limited by the size of the vacuum chamber (the diameter of the isolator could be > 1m).

c. Damping of lumped mass element (need to add damping in order to meet peak motion requirements)

- Q of lumped mass resonances (i.e. mass/spring modes) is approximately 100
- Damping may be accomplished using active means
- Passive tuned-mass dampers have been used for prototype stacks at UWA [3]

d. Damping of internal spring modes

- Lowest frequency of internal spring resonance is between 30–60 Hz and the Q is about 100
- If damping of internal modes is necessary, can mount isolator on extra stage of isolation such as the passive stack used for the initial LIGO.

B. Stack design

a. Design consists of 6 elements mounted in series. Each element is about .35 m high. Figure 3 depicts a 4 element stack; a partial representation of this design.

b. Size

- The overall height of the 6 stage isolator is about 2.1 m (83"). The diameter is .8m (31.5") for the curved stages and 1m (39.4") for the top stage

c. Determining number of elements and natural frequencies of stack

- Requirement for horizontal isolation of test mass is 10^{-10}
- Six stage 1 Hz multiple pendulum will achieve 7×10^{-10} horizontal isolation at 10 Hz. The 10^{-10} requirement is met when the 1 Hz test mass pendulum is included (i.e. attenuation becomes $7! \times 10^{-14} = 5 \times 10^{-11}$)
- Total stack vertical isolation needed at 10 Hz is 10^{-7} (assumes .001 horizontal coupling factor). Five stage cantilever spring-mass isolation system, with each stage having vertical resonant frequency f_o=2 Hz, will give attenuation of 1.5×10^{-7} at 10 Hz. A 6 stage isolation system meets the spec with 10^{-8} at 10 Hz.
- Effect of adding more stages

  More stages will make the roll off sharper and thus improve the performance not far from corner frequency. Yet this is again limited by the vacuum chamber; each extra stage will make the isolator .35m (14") taller. Besides, as one approaches a certain number of stages, there will be little gain by having more stages since the thermal noise crossing occurs around 10 Hz. Figure 4 gives a comparison of the performance for 4 stages verses 5 & 6 stages assuming that each stage has a natural frequency of 2 Hz.

C. Performance

a. The vertical performance of the 6 stage 2 Hz isolator is shown in Figure 4(c). The corner frequency is about 4 Hz. At 10 Hz the vertical attenuation would be 160 db (10^{-8}). The Q of each isolation stage was chosen to be 100. (It should be pointed out that adding the test mass stage will improve the vertical performance of the isolator only at frequencies above 15 Hz).

b. Horizontal performances of the 6 stage isolator pendulum (where each stage has a 1 Hz natural frequency) in series with a 1 Hz test mass pendulum are shown in Figure 5. The corner frequency is 5 Hz. The Q for each of the 6 pendula in the vertical isolator is chosen to be 1000 [3] while the Q of the test mass pendulum is assumed to be 10^6.

ii. DESIGN 2: 5 STAGE ISOLATOR + PREISOLATOR

A. Isolator Element Design

a. Configuration

- Same as for Design 1

b. Damping of lumped mass elements and internal spring resonances

- Preisolator provides extra attenuation at low frequencies so that high Q peaks for both lumped and internal resonances are below the isolation design goal. This means no extra damping is required.

B. Preisolator Design

a. Because of the relatively high Q of the all metal isolation stage, there will be high resonant peaks below the corner frequency. Very low frequency preisolation stage might be needed to lower these peaks, and also to suppress microseismic noise around 0.2 Hz. A possible horizontal very low frequency isolator is shown in Figure 6 [4]. Folded pendulum preisolator structures have been demonstrated to achieve stable operation at 0.1 Hz at UWA. They consist of an inverted pendulum combined with a normal pendulum and can be generalized to create a two dimensional horizontal preisolator if required. Vertical preisolation can be achieved using magnetic antisprings. Such systems have been demonstrated by Giazotto [5] and will be tested at UWA in 1994 (see Figure 7).

C. Stack Design

a. The design consists of 5 isolator elements mounted in series below a preisolator. A possible configuration is shown in Figure 7.

b. Size

- The overall width of stack and height for 5 elements is the same as for Design 1. The horizontal preisolator takes no additional space but the vertical preisolator could add as much as 20" (.5m) in height. The vertical preisolator replaces the first cantilever stage of the isolator in Figure 3, combined with a magnetic antispring structure. An additional isolator stage is therefore required (see Figure 7). Thus the total stack height, with an entire three dimensional preisolator would be 5*.35+.5=2.25m (89").

D. Performance

a. The horizontal performance of 5 stage stack + 0.1 Hz preisolator is shown in Figure 8. At 10 Hz the vertical attenuation is roughly 220 db (10^{-11})

b. The vertical performance of 5 stage stack + 0.1 Hz preisolator is shown in Figure 9. At 10 Hz the vertical attenuation is roughly 220 db (10^{-11})

IV. FITTING ADVANCED LIGO STACKS INTO PRESENT VACUUM CHAMBER DESIGN

i. Space in horizontal direction is adequate for both BSC and TMC chambers to accommodate advanced stack designs. There is 60" available and we need about 39".

ii. Assumptions used for calculating space available for vertical positioning of test mass in 4' clear aperture, given dimensions of advanced LIGO stacks

  A. Advanced LIGO test mass diameter = 20"

  B. Suspension length = 20"

  C. Vertical range estimates are done assuming that the z=0 position is 10" above the lowest vertical point in the 4' clear aperture (see Figures 10 and 11)

  D. Size of isolator measured from top of isolator to base of optics plate assuming each stage is about 35 cm (14").

    a. Design 1: 6 stages (35*6) = 210 cm = 83"
    (note that in this design the first stage takes no space)

    b. Design 2: 5 stages (35*5) + vertical preisolator (50cm=20") = 225 cm = 88"

  E. **Bound on maximum height from top of isolator to base of test mass for both designs is 20"+10"+88"= 118" (300 cm)**

iii. Vertical range for positioning test masses in BSC chambers

  A. There is 22" = 56 cm available vertically for positioning a 20 inch test mass (see Figure 10). This is 6" =16 cm short of the maximum usable space. This is an acceptable limit since the large test masses will most likely be positioned below the centerline of the 4' clear aperture.

iv. Vertical range for positioning test mass in TMC chambers

  A. Assume that the entire stack is lifted up into the dome so that the test mass clears the horizontal valve.

    a. Full range is possible for positioning the large test masses (See Figure 11). In fact there is 28" = 71 cm of unused space above the stack.

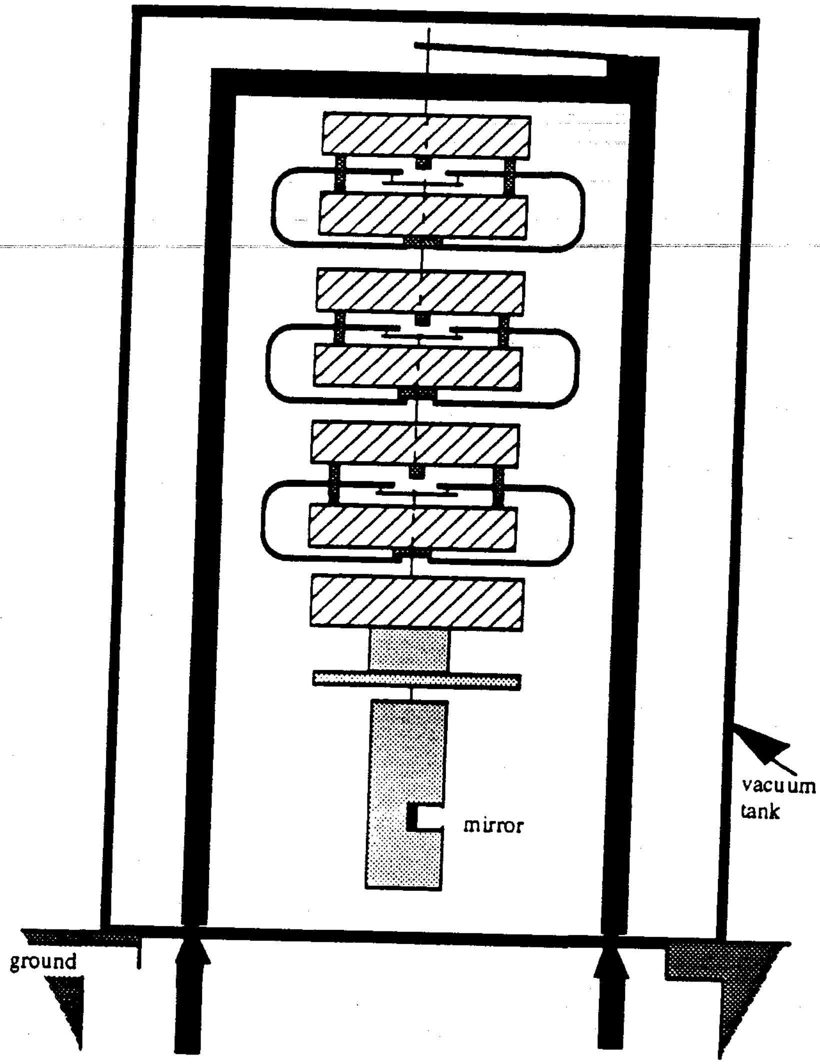

Figure 1. Current University of Western Australia Vibration Isolation Design

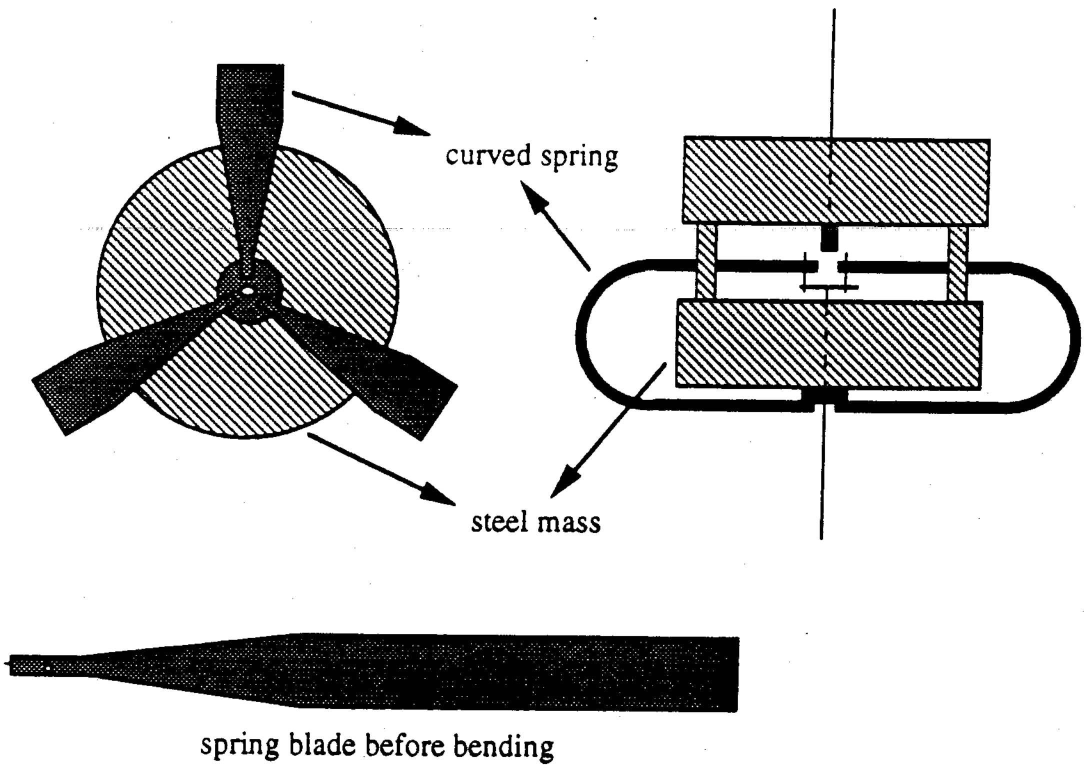

Figure 2. Configuration of 1 isolator element.

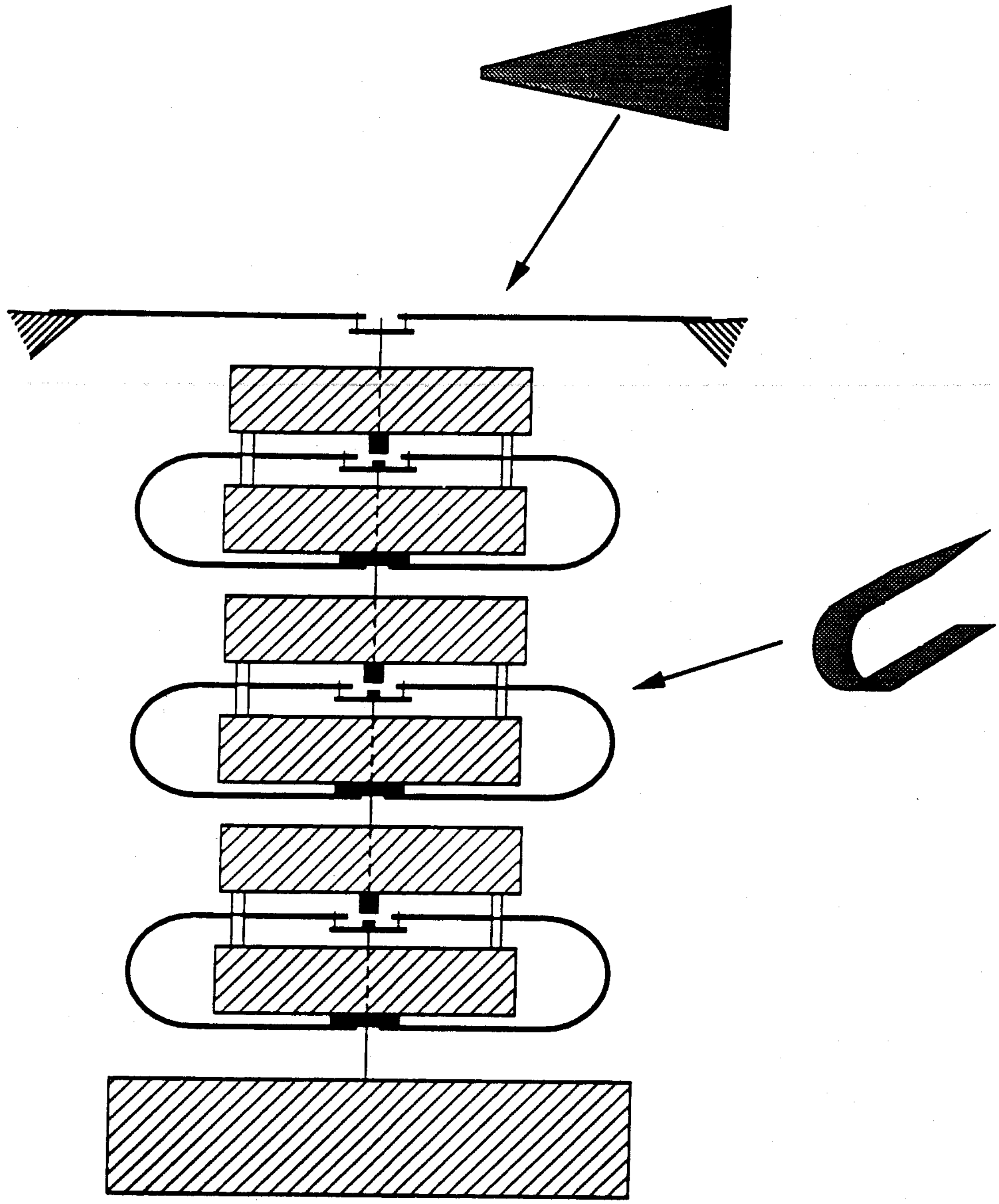

Figure 3. Four element stack.

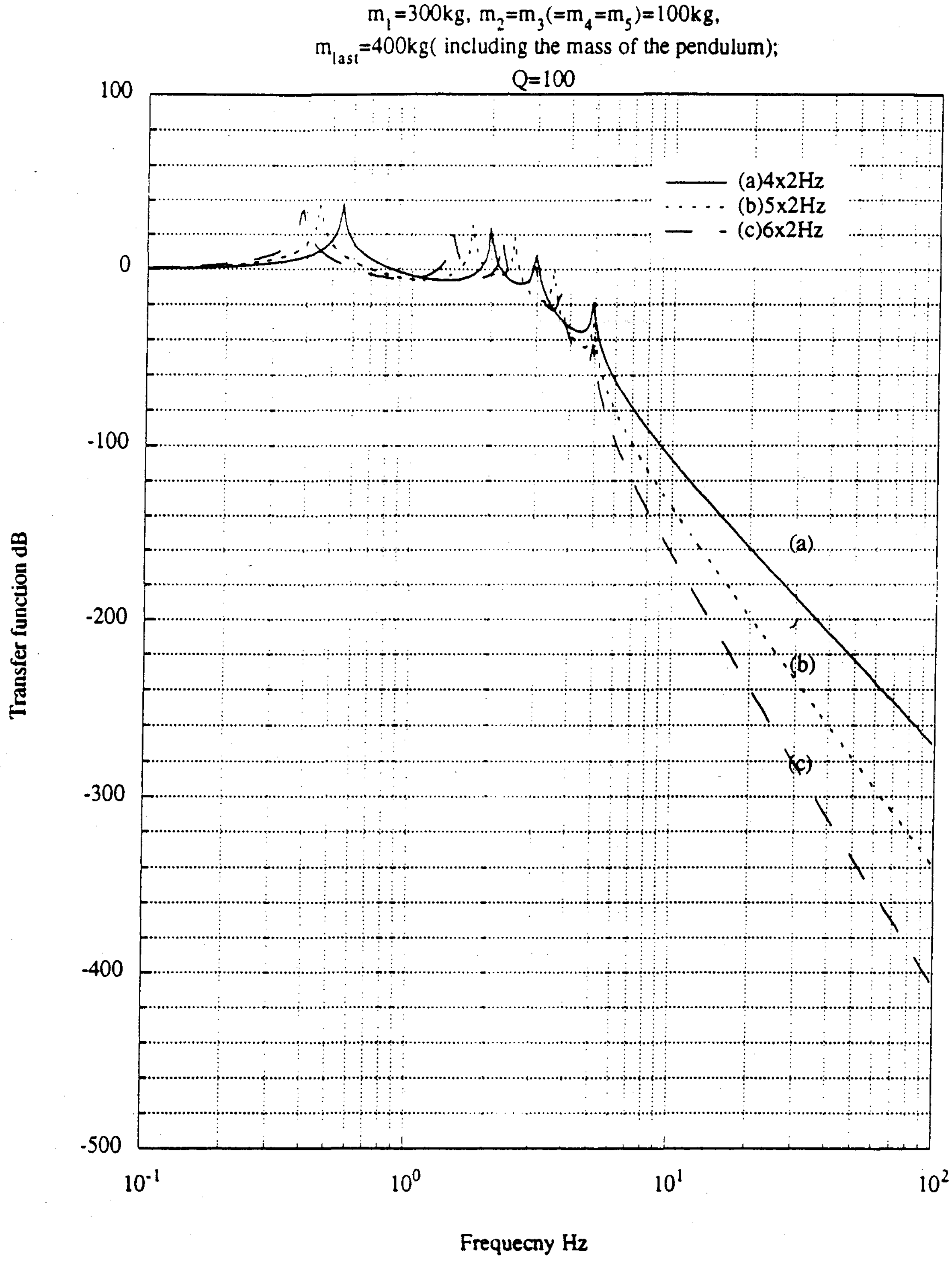

Figure 4. Comparison of vertical isolation performance for a 4, 5, and 6 element stack design.

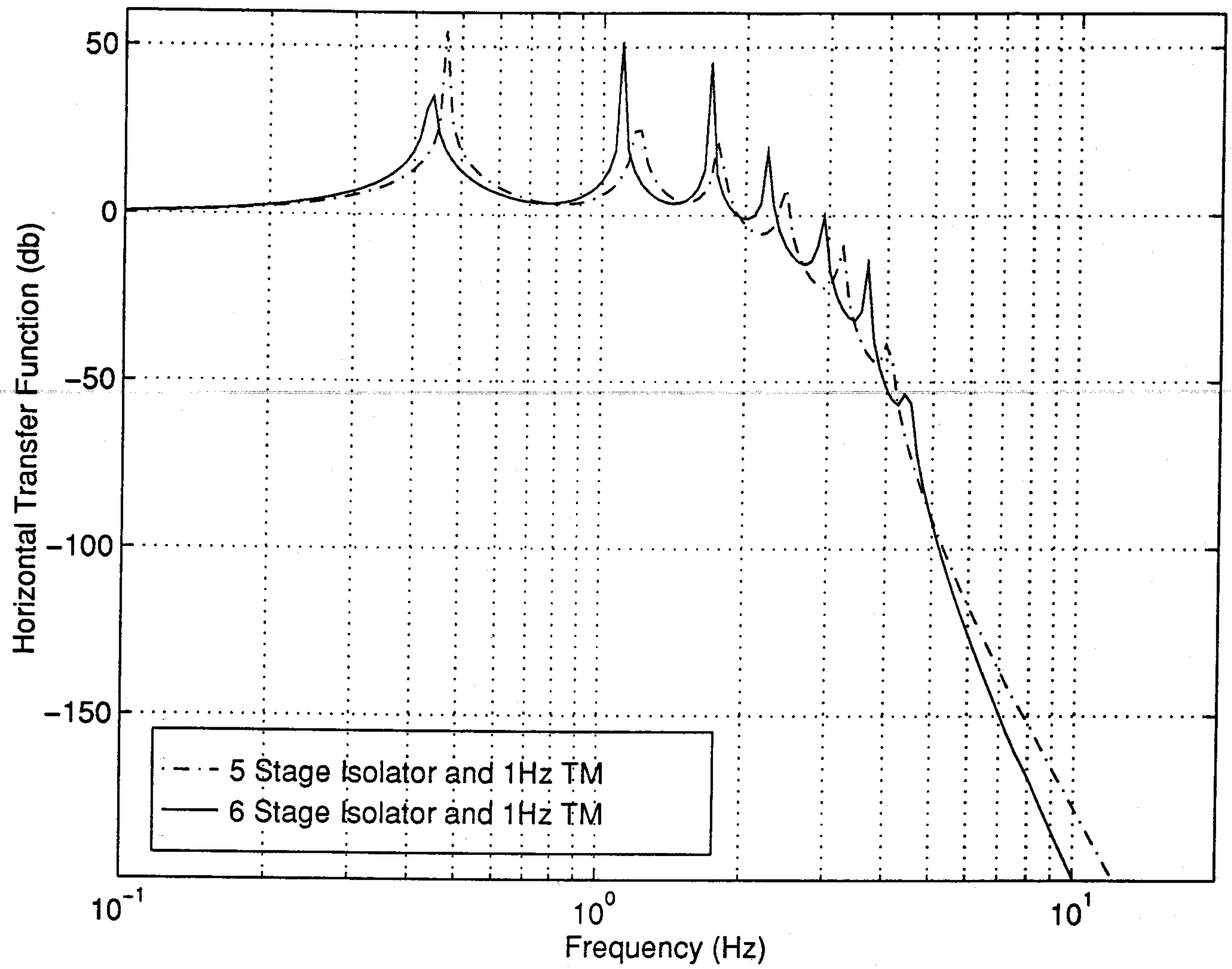

Figure 5. Comparison of the horizontal isolation performance of a 5 and 6 stage 1 Hz pendulum Isolator (both plots also include the effects of a 1 Hz test mass stage). The parameters used in the model were as follows: m1=400kg, m2=m3=m4=100kg, m5=m6=200kg, and Q(all)=1000.

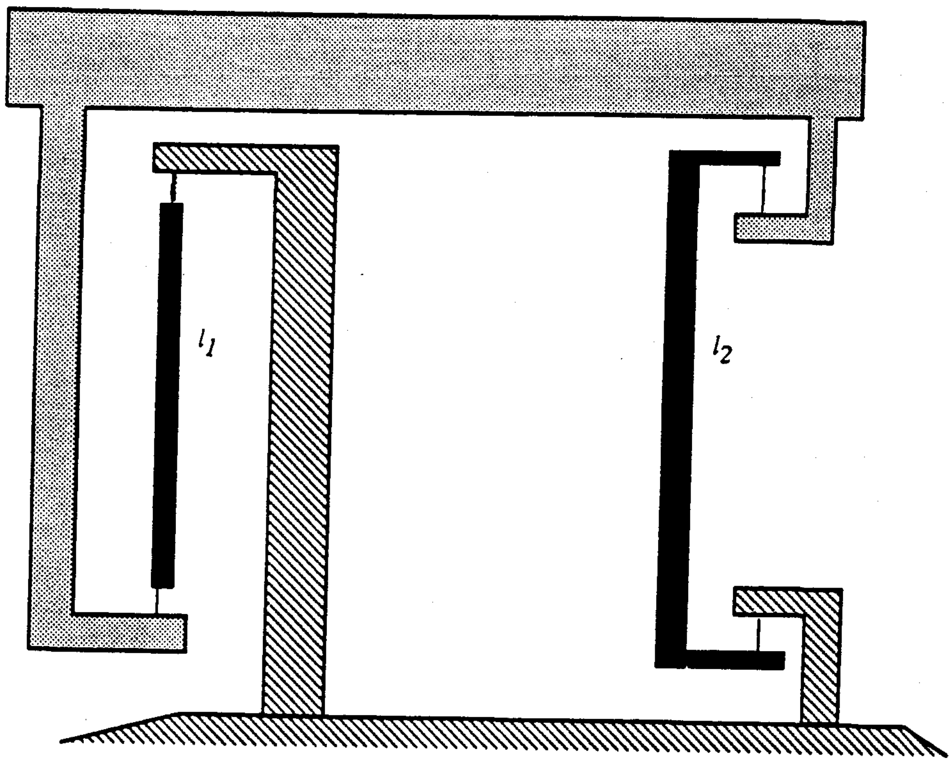

Figure 6. Possible design for a horizontal preisolator: a folded pendulum structure.

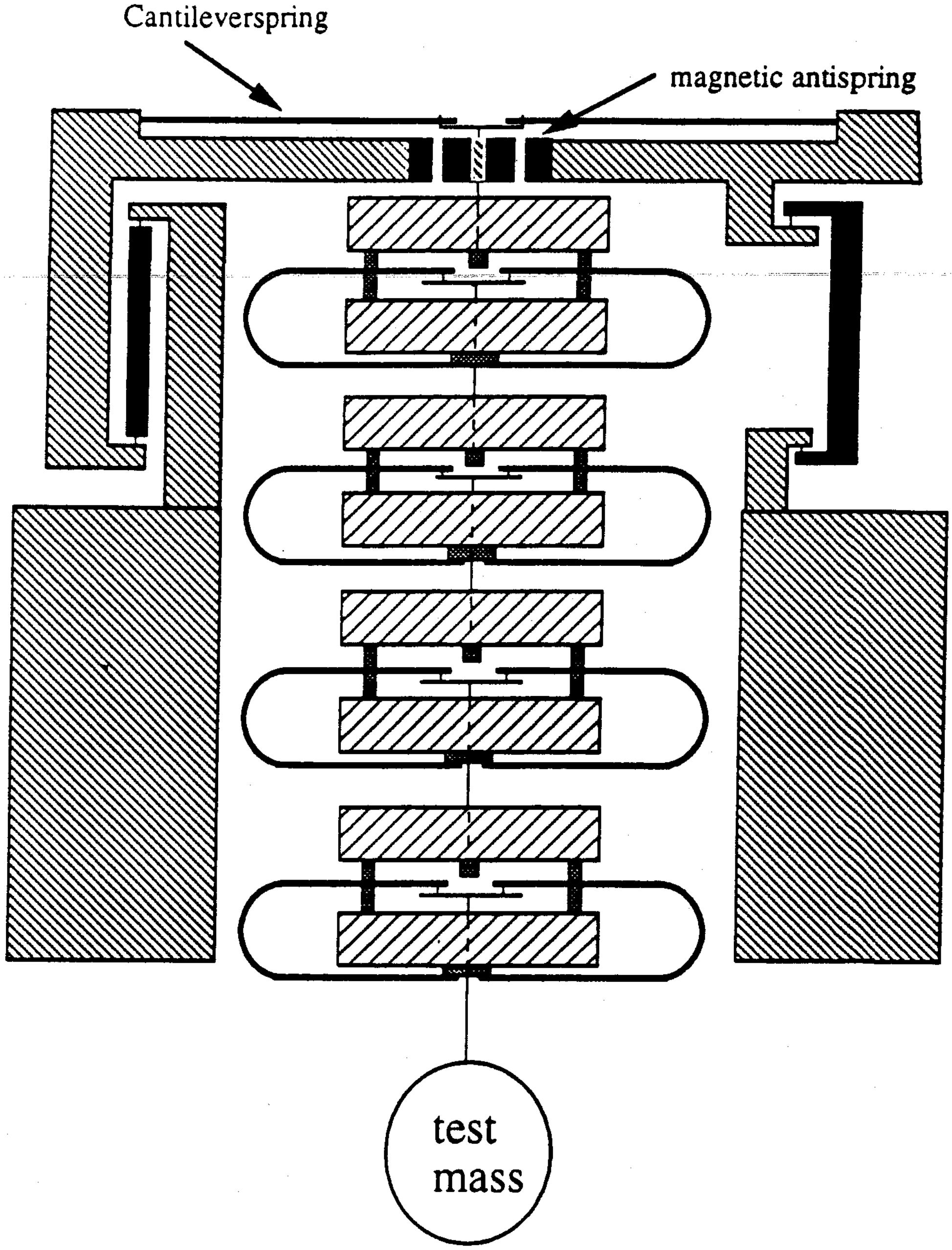

Figure 7. Possible configuration for a four stage stack design with a preiosolator.

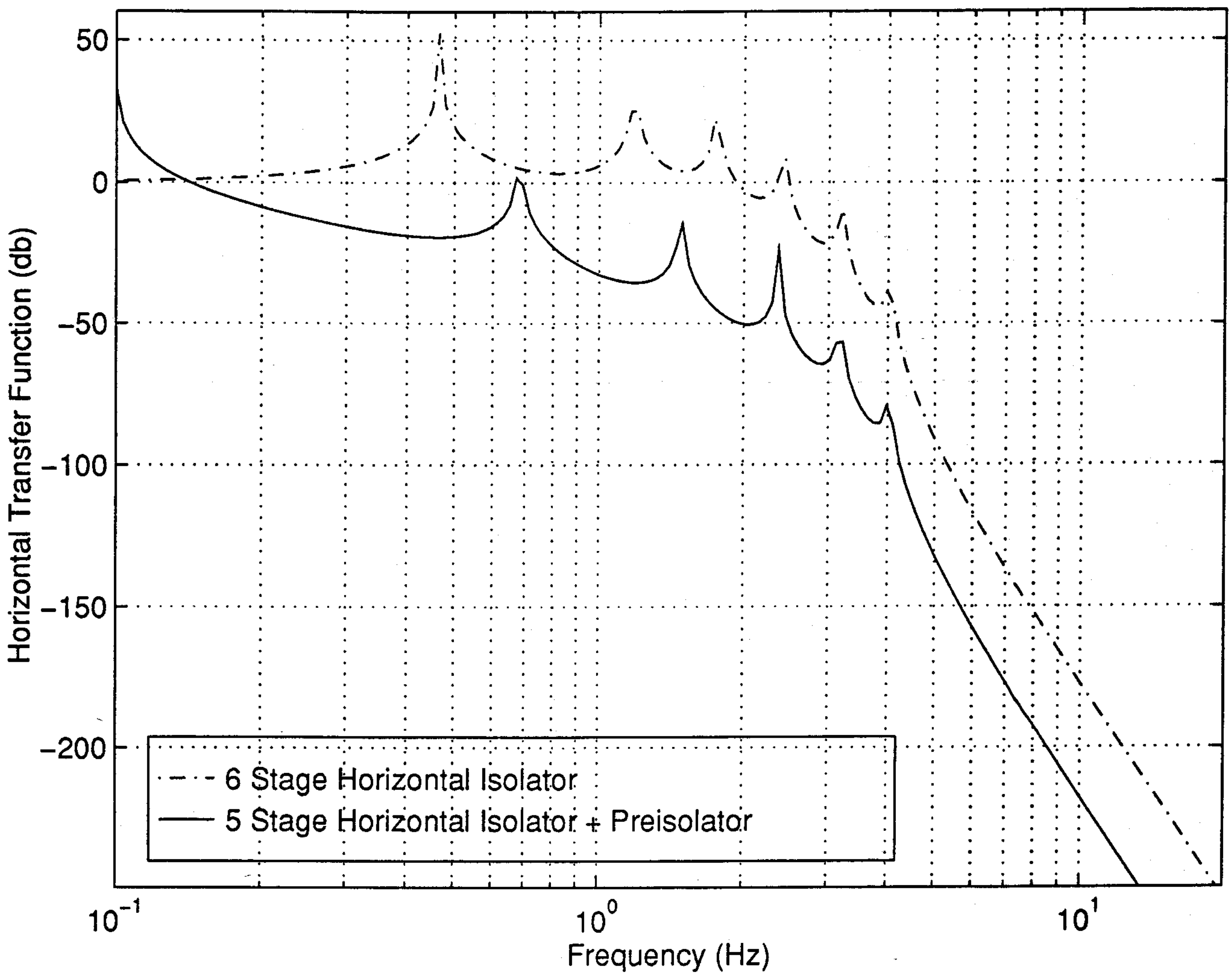

Figure 8. Comparison of horizontal isolation performance for a (6 stage stack) and a (5 stage stack + preisolator). Does not include effects of test mass stage. Does not include the effects of test mass stage. Parameters used in model were: m1=400kg, m2=m3=m4=m5=100kg, m6=200kg; Q=1000, fo=2Hz, f(pre)=0.1Hz

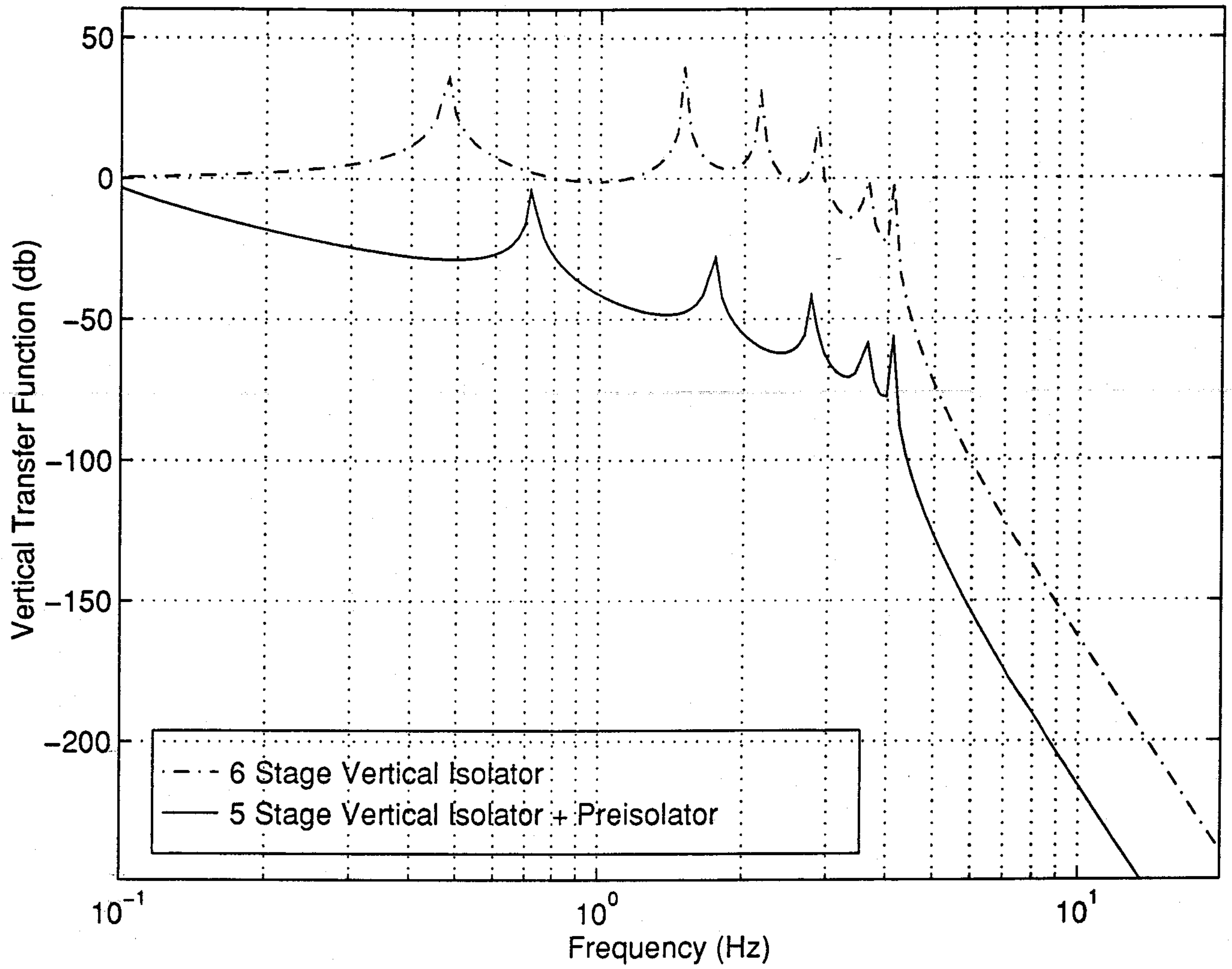

Figure 9. Comparison of vertical isolation performance for a (6 stage stack) and a (5 stage stack + preisolator). Does not include the effects of test mass stage. Parameters used in model were: m1=400kg, m2=m3=m4=m5=100kg, m6=200kg; Q=1000, fo=1Hz, f(pre)=0.1Hz

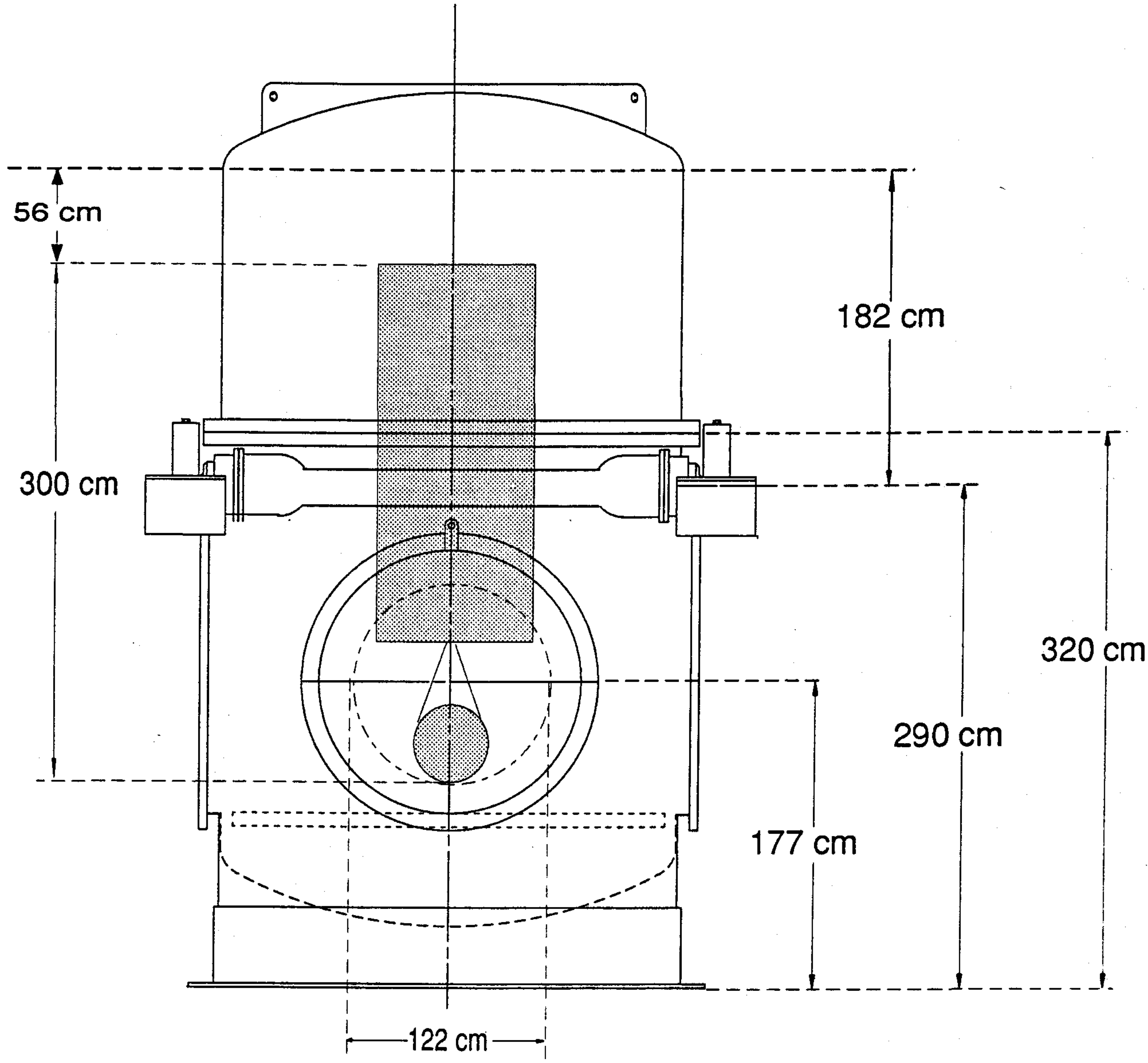

Figure 10. Drawing to show dimensions of the BSC chamber and how an advanced design will fit into chamber. There are 56 cm available vertically for positioning the test mass. This is 16 cm short of the maximum usable space. This is an acceptable limit since a 20 inch test mass will most likely be positioned below the centerline of the 4 ft clear aperture. The drawing number for the chamber is 1101009, revised 9/14/94 by KDR.

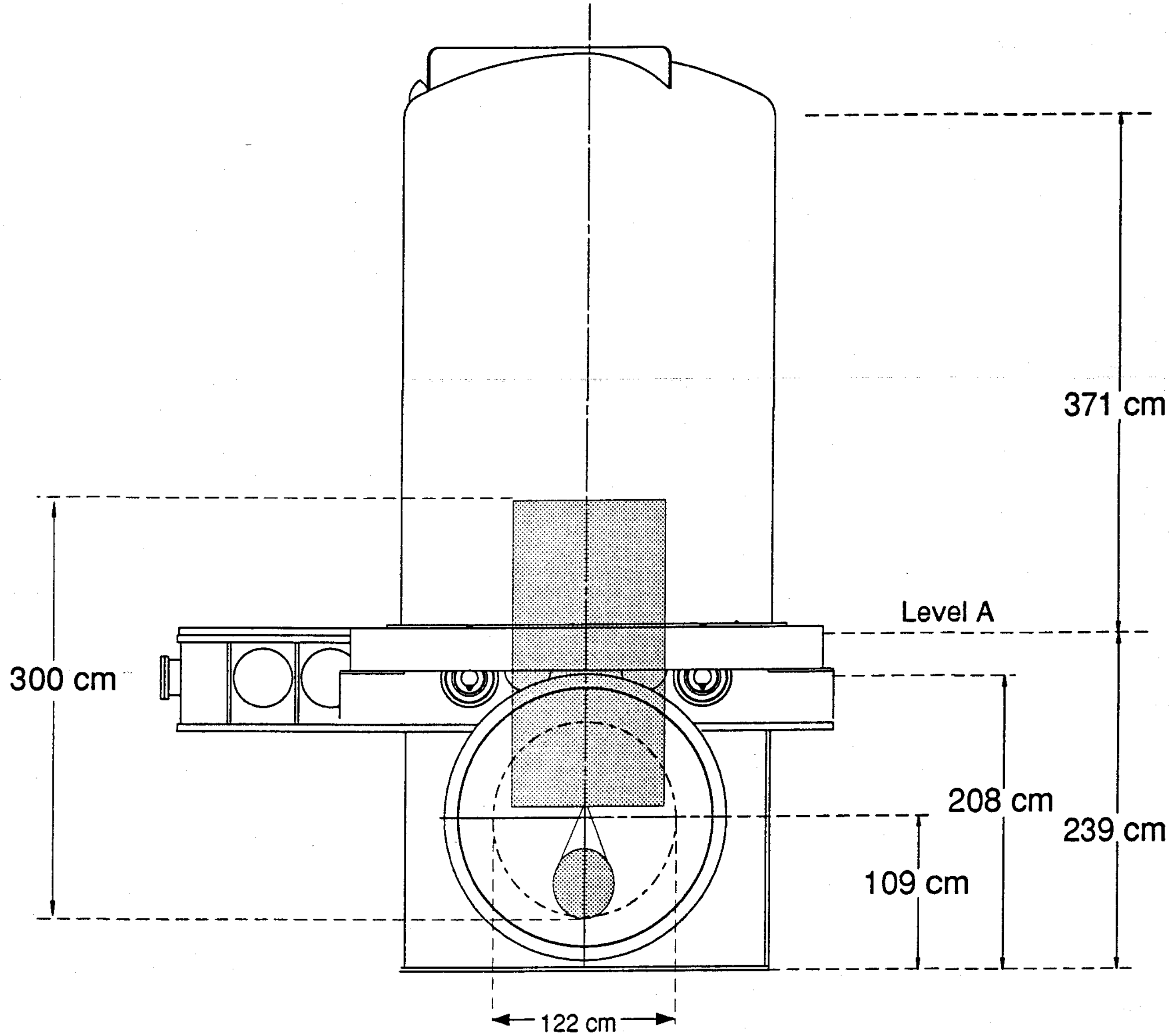

Figure 11. The drawing shows the dimensions of a TMC and how an advanced design will fit into a TMC chamber. The drawing shows that full range is possible for positioning a 20 inch test mass in a TMC chamber. When the stack and test mass are positioned inside the dome so that the test mass just clears Level A, there is still 71 cm of unused space above the stack and 45 cm of space between the top of the horizontal valve and the bottom of the test mass. The chamber drawing number is 1101013 and will probably be revised (KDR 9/26/94), but the revisions change the conclusions by only a few cms..

Bibliography

[1] J. Li, D. Blair, and F. van Kann, "Novel isolation and suspension systems for laser interferometer gravitational wave detectors," in *Proceedings of the International Workshop on Experimental Gravitation*, (Nathiagali, Pakistan), 1993.

[2] *NSF Proposal: A Laser Interferometer Gravitational-Wave Observatory*, vol. 1. December 1989. page 56.

[3] D. Blair, L. Ju, and H. Peng, "Vibration Isolation For Gravitational Wave Detection," *Classical and Quantum Gravity*, vol. 10, p. 2407.

[4] F. J. V. Kann, "A Folded Pendulum Very Low Frequency Mechanical Resonator," in *New techonology for Gravitational Astronomy*, Perth, 1993.

[5] A. G. at INFN. Private communication with Ju Li during trip to Pisa in 1993.