BODY WAVE TRANSMISSION REDUCTION OR ELIMINATION BY PASSIVE DYNAMIC MECHANISM USING AUTOMATIC CONTACT POINT EVASION METHOD

An innovative device, called *Aurios bearing*, have been developed to reduce body wave transmission in electronic equipment supports or legs, thereby enhancing the quality and performance of said equipment, especially of media players, recorders and related ones. The bearing's recent commercial introduction generated great demand in sales and in explanation for "Why is it so effective?" This short article aims to answer that question.

Body waves self-induced within said equipment, reverberating within -- without draining off -- reduce sound and picture quality by adding noise and unwanted resonance or amplifications and interference. Current equipment legs can drain away some of said waves by isolation or damping, while the *Aurios*, almost all of it by deflection and evasion. Draining effectiveness of current legs ranges from 20 to 80%, while the *Aurios'* one is from 99 to 99.99% as demonstrated by experiments (see Appendix A). Current legs also add a specific unwanted noise to the sound or picture, but the *Aurios* does not.

For illustration an *Aurios™ Media Isolation Bearing*, manufactured by Vistek, Inc. is shown here. Note that one equipment rests on three bearings.

The *Aurios* contains three ball bearings in dimples or in raceways (not visible in the picture). The balls and the raceways are highly hardened and smoothened alloy, stainless, metal-glass or ceramic parts. The bearing shown above is about 40-mm in diameter, 20-mm tall and can carry 150-kg payload. It is a thrust bearing with nonlinear gravity restoring capacity, having a pseudo-natural frequency less than one second. As such, it works as an excellent vibration isolator. Yet, that alone would not account for the remarkable performance, which makes this bearing outstanding. So how does it work?

Noise propagates in solids in tension-compression waveform or in wavelets. Note that wavelets are short duration waves separated by longer duration silences. For convenience, engineers plot the amplitude of such longitudinal waves perpendicular to the time line to look like transversal waves. However, keep in mind that for sound waves in gas -- such as air -- or in solids -- such as equipment legs -- the wave amplitude is collinear with the wave propagation direction. Whether such wave stay focused and travels in straight line or will be dispersed and bent, is the function of the solid's material properties and microstructure, such as crystalline, amorphous or mixed. It also a function of other factors, such as temperature and stress distribution or gradients and surface conditions. The light ray to sound wave analogy may be helpful here:

Remember that when light ray enters a glass lens, prism or ball, it bends, scatter, reflects, refracts, diffuses and diffracts. That is, only a small fraction passes through straight. That allows the creation of sophisticated optical instruments in which the light goes exactly where the engineer directed it by design. Lenses, prisms and balls all have their equivalent devices in sound transmission and are used in the *Aurios*. For instance, the ball under load in contact with a dimple or raceway is equivalent in sound transmission to a prism in optics. That is because near the contact, the pressure gradient changes fast by the distance. So does the local density and the sound wave propagation speed, resulting in reversed propagation bending in the ball and the dimple by different amount, proportional to the ball and dimple radiuses.

Now, back to the sound drainage in solids problem, which means directing the waves towards and then through a sufficiently small exit point. The smaller is the exit area, the less chance for back propagation. A fiber optic is a good example of a wave-guide for light ray and a trumpet for sound wave. A needle point or cone equipment leg is a case in point. An other one is the wire suspension. Their only weakness is that as many waves can exit through their contact point, the same amount can enter in reverse. Since much of the waves passed already are lost before can reenter, these are proved fair to good sound sinks or so called isolation legs. How can the *Aurios* be even better?

By an elegant twist: <u>By the time a reentry would occur, the contact point had already shifted away!</u> That does not mean that nothing would go back. It only means that the same wave or wavelet reflected can not reenter to reinforce the signal by interference resulting in amplification. That is, the chance for positive feedback is eliminated. Now, that sounds easier to say than to do. So how did *Aurios* achieve it?

Firstly, by selecting spherical shape for wave-guides rather than conical ones, namely balls. A ball indents upon contact and pressure in a circular area, which is extremely small in diameter relative to the ball diameter. Direct wave passage is possible only in the theoretical cylinder, which connects the contact points on the opposite ends of the ball. In essence, this wave-guide is equivalent to a thin wire.

Secondly, by sandwiching said balls between concave dimples or raceways, which makes the assembly an isolator with a narrow-band peak-response or with a real or a pseudo natural period. That makes possible a ball oscillation with a known, designed frequency. So when the ball oscillate, it constantly shifts its contact point locations. If that shifting time, the oscillation's period is smaller than the time required for the sound wavelet to cross the ball, direct back propagation is eliminated. (See Appendix B.) In other words, the back propagation path is evaded. The only thing is needed for constant operation is a steady vibration source, which would make the ball oscillate. Experience shows that -- since the contact diameter is very small and thus the required oscillation amplitude is very small too -- even ambient vibration is a sufficient source. However, the equipment themselves have often higher level of vibration while operate, then their ambient. So the said evasion is automatic and the *Aurios* is self-reliant or in other word, the *Aurios* is an automata, an evasion machine.

Thirdly, by engineering the bearing to perfect said evasion. That is using exotic hard materials. Using high-tech surface finishing and heat treatment technology, raised contact perimeters and other manufacturing and design tricks the industry can deliver today on reasonable budget as well as proper sizing the components.

To close this short introduction, let us refer back to the title: The *Aurios* is an isolator but much more than that. It is a passive mechanism, because it constantly moves, but it needs no external power source to maintain that movement. Said movement is necessary to its operation. Its source is ambient, which includes the equipment and its support. It is called passive dynamic, because movement makes it work and that movement is not activated by added energy source. It evades the back propagation path of any wavelet passage from equipment to support or in reverse. More precisely, it evades automatically the reentry contact points through which a wavelet --reversed in the support or in the equipment base -- could return and reinforce itself by positive feedback. It works equally on wavelets and waves. Its condition of operation is expressible in closed formula of the material and geometrical properties alone. Thus, its design is controllable and repeatable. It does not add a specific noise to the equipment sound or picture because it has no permanent contact points, but rather evasive ones.

Attachments: Appendix A, "Experimental Results."
Appendix B, " Theoretical Considerations."

APPENDIX A

Experimental Results

At TGE we conducted comparative testing of a common rubber isolation device and the *Aurios* bearings. Dynamic Labs, L.L.C. an independent testing agency in Phoenix, AZ performed the tests and the results are submitted below.

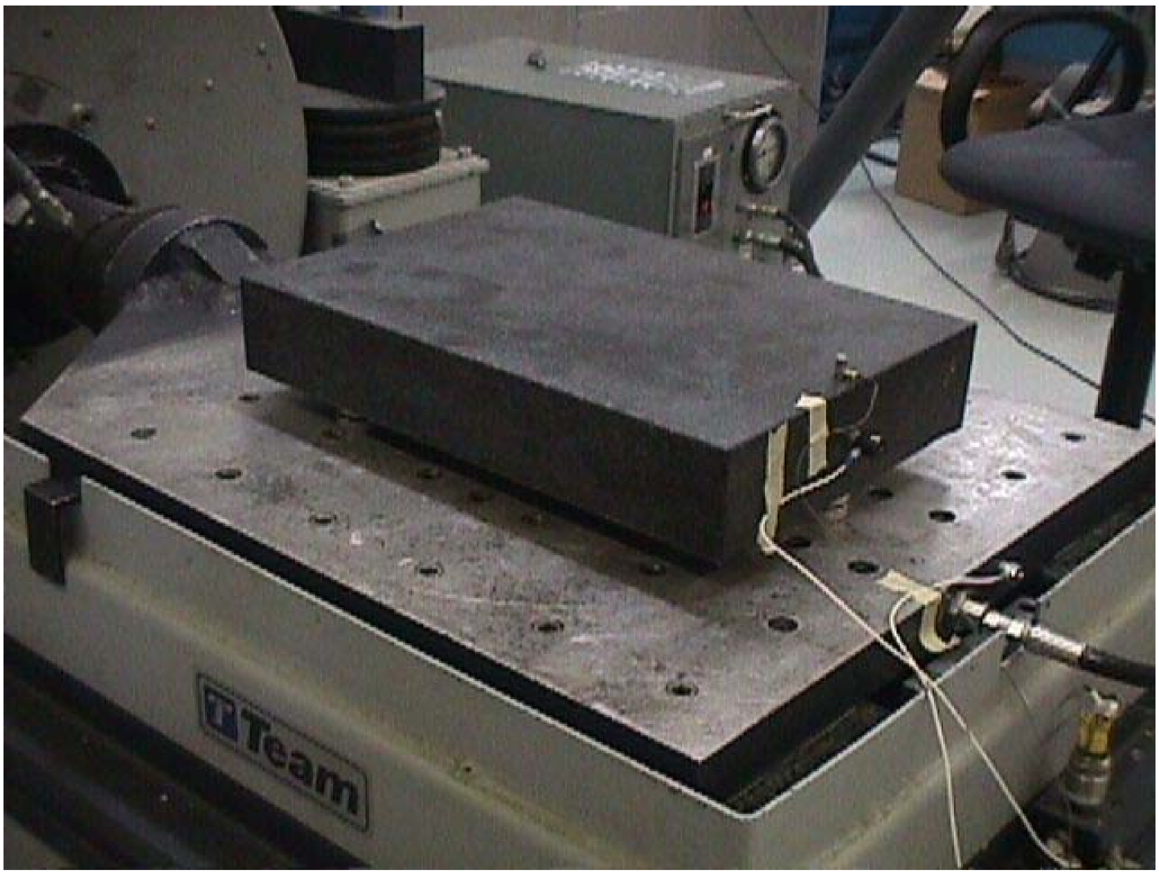
The rubber bearings were close to 2-1/2” diameter and 3/4” high, with rated load capacity of 8 lbs. The *Aurios* bearings were about 1-5/8" diameter and 7/8" high, with rated load capacity of 330 lb. The carbide balls were hardened to Rc80 and the raceways to Rc60. For payload, we used rigid granite plate weighing 18 lb. for the rubber and 75 lb. for the *Aurios* bearings. The payload, representing the equipment weight, rested on three bearings in both cases. A general overview of the testing setup is shown below.

The shaker is a 10-ton giant loudspeaker visible on horizontal axis on the rear floated on air bearings visible on the left. To the center coil a 1-ton large granite table floating on pressurized oil bed is attached. The oil is pumped and cooled by an aggregate visible on the right separate from the table. The shake table granite is lined on top by a 1" thick stainless steel matrix bed to receive payload attachments. Centered on top of the matrix bed the granite plate payload rests just by gravity on three rubber legs (not visible here). A large accelerometer is glued to the payload granite plate on horizontal axis collinear with the shaking of the support. A smaller accelerometer is glued above larger one measuring in vertical direction for checking mid-span plate deflection and vertical response due to horizontal excitation. The vertical effects were found to be negligible. Control and measurement (data acquisition) signals were connected to a central computer (not visible here), where the data was processed on line and documented later off line. The laboratory is on the first floor on concrete slab on grade in an off traffic road to ensure quite base from ambient noise and vibration.

We chose constant 0.0063" displacement amplitude forcing swept from 5 Hz until we reached 1g acceleration. Then we swept further onto 500 Hz keeping 1g constant acceleration and reversed the sweeping back to 5 Hz the same way in reversed order. (Note that 1g = 386 in/sec/sec and the transition corner frequency was 39.36 Hz. The sweep lasted 7min up and 7 min down.)

On the spectral plots next, the constant acceleration sweeping appears as an ascending line and the constant acceleration one as a horizontal line. The spectral plot abscissa is in the 5-500 Hz range and the ordinate is in variable scale in units of g, according to the actual measurements. Both the abscissa and the ordinate are in logarithmic scale. We will present here first the input and output acceleration spectra for easy comparison for both setups (bearing types). Secondly, we present the output-per-input response spectra, which called the transmissibility curve. The plots are clearly labeled, including the bearing types. The rubber bearings were considered generic and arbitrarily labeled as Vibropod 2.

Below is the setup for the *Aurios* bearing testing, which is the same as the one for the rubber bearing testing, except with a larger granite payload.



Next, the *Aurios* bearing on the left is compared to the rubber bearing on the right.

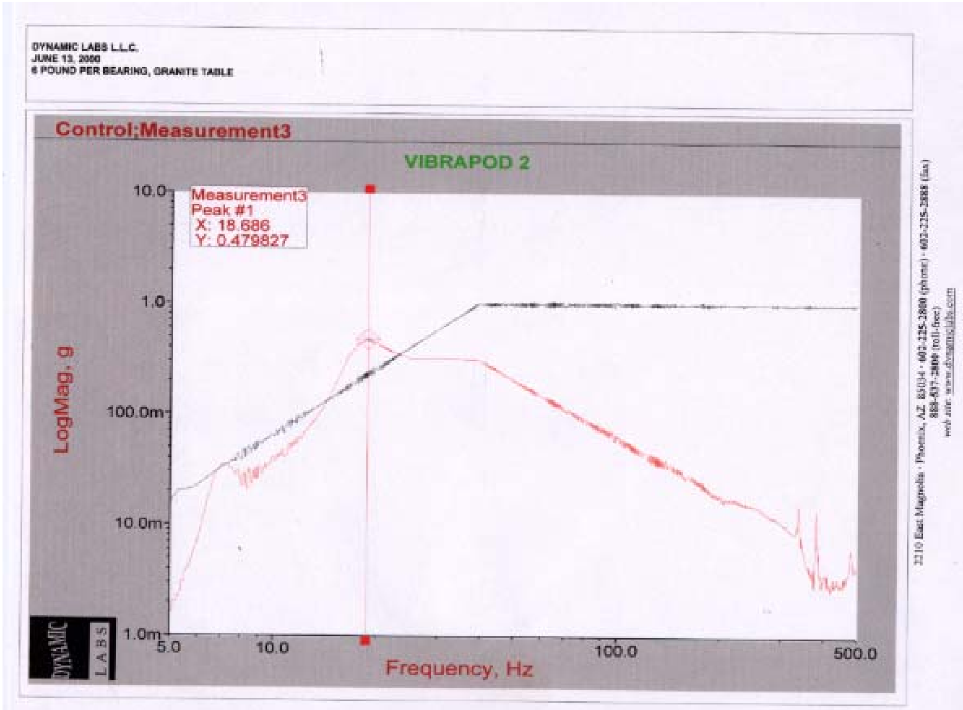
Next, the laboratory is shown with the computers included. In front with an operator the data acquisition one and on the rear, left to the shaker coil, the big cabinet is the control computer system. The coil is cooled with forced air system, which is located in an other room, thus not visible here, except its air duct on the left of the control cabinet.

In the followings we will present, compare and explain the plots obtained by testing.

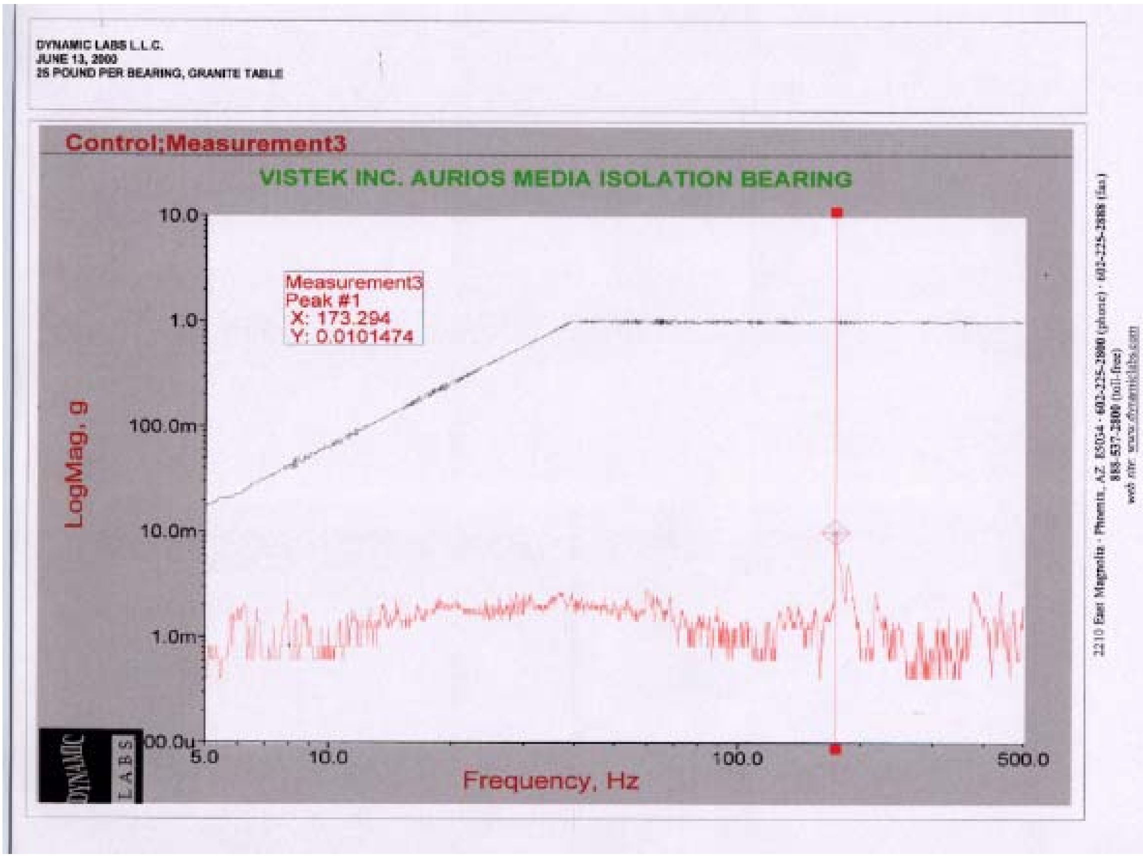
Plot 1 next is the rubber bearing's collinear response (input-output) spectra, which is to be compared to that of the *Aurios'*, shown next on **Plot 2**.

The rubber bearing has double peak response above input level at 7.3 and 18.7 Hz. The second peak is closer to a typical rubber bearing's natural frequency. Rubber bearings resonate at the 15 to 30 Hz range. The rubber bearing amplified input acceleration by two folds at resonance, indicating good damping characteristics. The output curve crosses over the input one at 23 Hz, from where it continues with constant acceleration up to 30 Hz, from were on declines steadily. This response is typical to isolation legs, especially of the soft spring suspension type legs, such as this rubber leg is. This bearing reached better than 99% isolation level only beyond 330Hz. This makes it suitable to generic mid-fidelity audio equipment application. Its 18.7 Hz resonance frequency is almost audible, which excludes its high-fidelity application. The first peak and the flat (constant acceleration) response is peculiar to this bearing having an accordion like cross section.

The *Aurios* bearing's response is flat all over the spectra averaging at 99.9% isolation level. The response peak is non-characteristic at an arbitrary frequency (173 Hz). The response floor is at 99.99% isolation level. The *Aurios* apparently has no damping. This outstanding performance renders this bearing suitable to high-fidelity application.



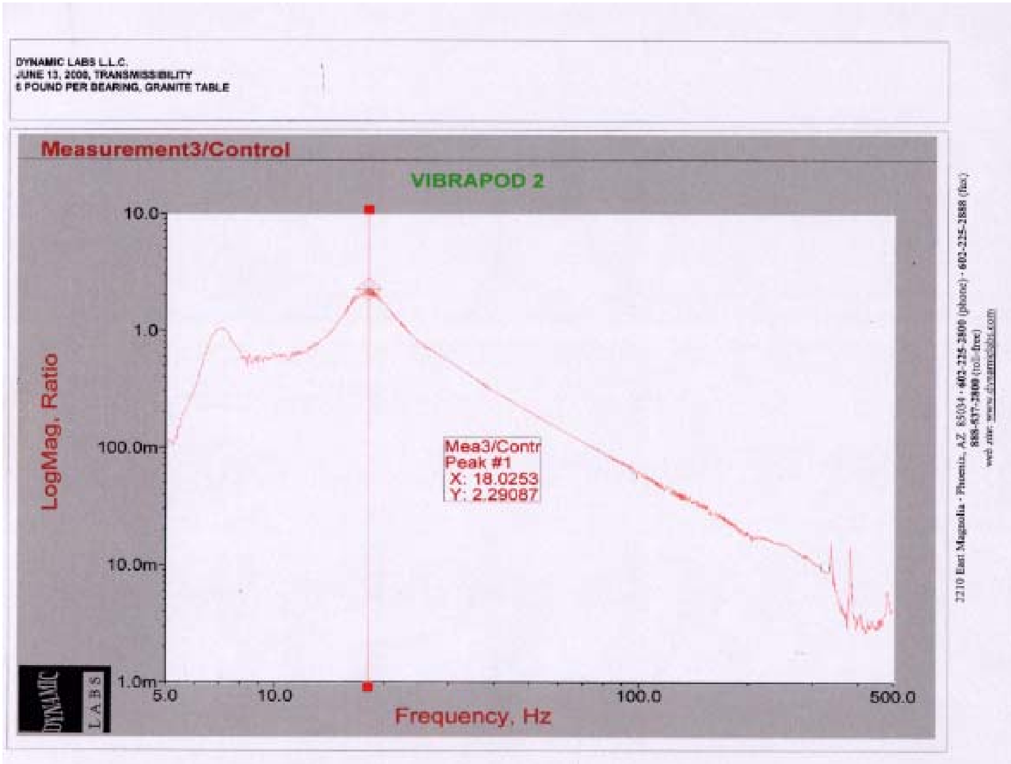
Plot 1 Input acceleration (black) and output acceleration (red) spectra for rubber bearings



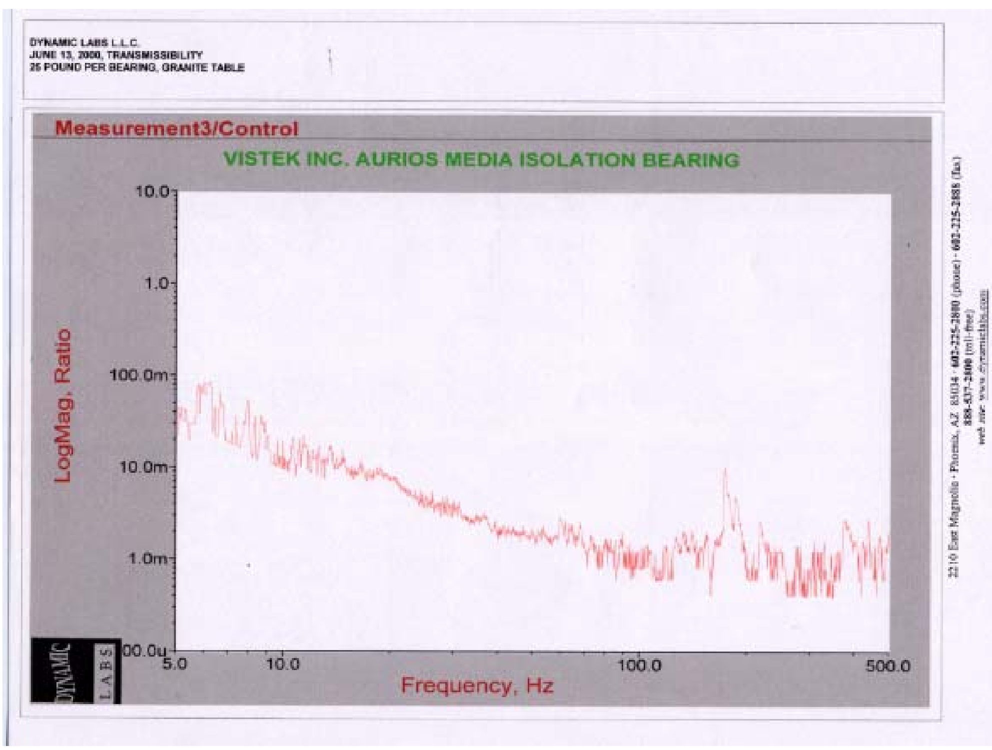
Plot 2 Input acceleration (black) and output acceleration (red) spectra for *Aurios* bearings

Plot 3 next is obtained from Plot 1 by dividing the output acceleration ordinate by the corresponding input one at every frequency. The first peak is at 7 Hz with 0% amplification or isolation and the second peak is at 18 Hz with 230% amplification. The bearing does not isolate (rather amplifies) in the 14-21 Hz range. 20% isolation is achieved below 5.7 Hz and above 50 Hz. 90% isolation is achieved below 5 Hz and above 73 Hz. 99% isolation is achieved beyond 310 Hz. The best isolation level of 99.7% is reached at 410 Hz.

Plot 4 next is obtained from Plot 2 by dividing the output acceleration ordinate by the corresponding input one at every frequency. Compared to Plot 3, Plot 4 appears noisier, thus best judge by the average of its random variations, which yields to a smooth curve (not shown). Such smooth response curve declines steadily from 87% isolation level at 5 Hz to 99.9% at 100 Hz, beyond which stays at that level flat. The actual plot's peak is at 173 Hz with 99% isolation. This peak is seemingly at a random location, just rising off from noise, not associated with resonance at all. The best isolation is also at apparent random location (170 Hz) reaching the 99.97% isolation level.



Plot 3 Transmissibility spectra of rubber bearing

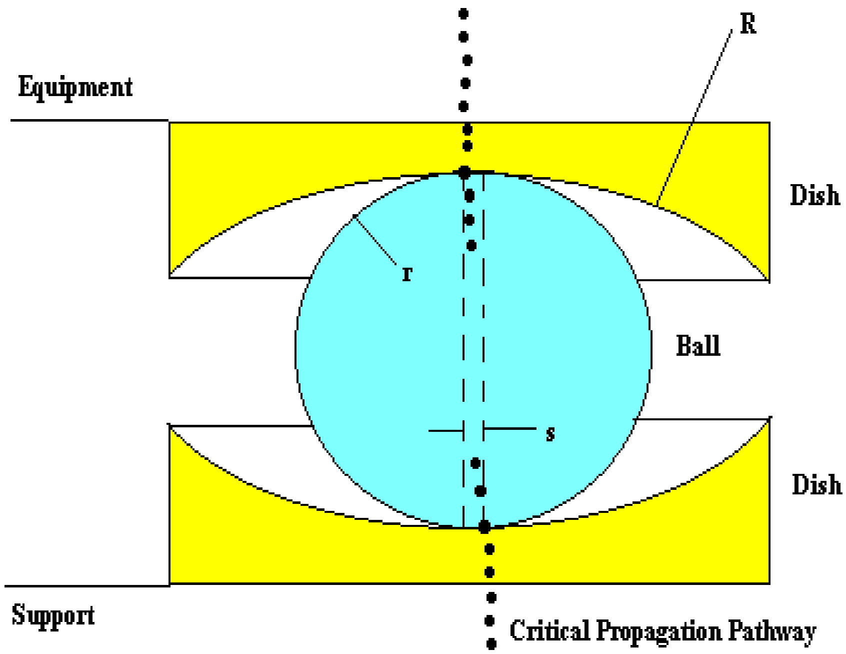


Plot 4 Transmissibility spectra of *Aurios* bearing

APPENDIX B

Theoretical Considerations

Consider a ball sandwiched between dimpled pates (dishes) as illustrated in **Fig. 1** below.



Under the equipment load the ball and the dishes indent in a circular footprint of diameter **s**. The ball radius is **r** and the dish radius is **R**. There is a theoretical tube as a wave guide inside the ball -- shown dotted -- of diameter s and length 2r. The critical pathway of a sound wave to pass in full strength is shown bold dotted as the diagonal inscribed in the theoretical tube. Note that the tube is only theoretical, since a real one would have a cylindrical surface. From such a surface, a wave entering in larger inclination angle would reflect several times and stay within the tube, finally exit and enter to the other dish. In reality, there is no such physical tube within, so a higher inclination wave would simply be reflected within the ball surface and may never lave the ball. The wave is considered longitudinal (tension-compression) type. The coupled transversal waves -- being relatively small -- are neglected here, but not in the second order analysis.

Suppose the ball rests between the dishes and a wave passes through downward right at the center of said theoretical tube. Since the contact makes the ball a common body with the dishes at the contact surfaces, said wave -- called trivial wave -- could reflect, back propagate and interfere with the oncoming wave. Than again and again, up and down. This wave reflections would be very similar to light wave reflections in a laser diode. If the distance between the back of the dishes (the support-equipment distance) or the ball diameter is the multiple of said wave's wavelength, we would have a "sound laser" defying the purpose of noise transmission reduction. However, if the ball would roll off before the reflection wave – once reversed -- could exit within the same contact area it entered, we would have a silent wave trap instead. Indeed, this is the principle of dynamic wave evasion by contact shifting, a principle the *Aurios* bearings are constructed. One may notice that this bearing assembly -- when left unattended after brought into lateral motion -- acts like a pendulum, capable to oscillate by a single period, the so-called natural period. Therefore, if some steady source of lateral motion is present and the assembly is designed properly, the assembly can block almost all wave passage and act like the perfect isolator in sound transmission. Fortunately, the required oscillation amplitude of said pendulum is very small (equal s, the diameter of said theoretical tube). Thus, even the excitation generated within the equipment -- its own noise -- could be sufficient to keep said pendulum in steady or random oscillation. According to practice and controlled experiments, that is the case with the *Aurios* bearings used in media equipment.

The trivial wave passes unweakened and undistorted. The critical wave passes unweakened but distorted. Said distortion is directly proportional to the wave intensity and inversely to the modulus of elasticity of the ball or dish. The distortion is also affected in lesser amount by the surface hardness and smoothness of the ball and dish. Any wave between these two waves is subcritical and passes unweakened but distorted. Any wave not mentioned here is supercritical and may pass weakened and distorted or not pass at all. Waves entering the ball in positive critical inclination and leaving in negative one after one reflection are the design waves. A design wave passes unweakened if the contact area shift during said reflection is the diameter of said area. The distortion of a design wave is not considered.

Next we will study said evasion condition and establish said proper design criteria based on the design wave.

The sound propagation velocity in solids is derived from

$$v^2 = E/\rho \qquad (1)$$

where v = propagation velocity
E = modulus of elasticity and
ρ = density of the solid.

The natural period of the assembly as an isolator (equivalent pendulum) is obtained from

$$\omega^2 = g/L \qquad (2)$$

where ω = circular frequency of isolator (equivalent pendulum) = $2\pi/T$ where
T = natural period
π = 3.14 and
L = equivalent pendulum length = $2(R-r)$ for dimples and
g = 386 in/sec^2.

The ball indentation diameter in the dish is derivable from

$$s^3 = 2^{3/2}PKC \qquad (3)$$

where s = indentation diameter
P = load (weight) on the ball
$K = Dd/(D-d)$ where $D = 2R$ and $d = 2r$
$C = 2(1-\nu^2)/E$ where ν = Poisson's ratio
all in reference to the ball and dish assuming the same solid for both.

The evasion criteria is

$$2d/v > s/\omega L \qquad (4)$$

By substitutions of (1) through (4) and rearrangement, we can solve for any variable. For instance,

$$P < MG \qquad (5)$$

where M = material factor = $\{\rho g/[(\nu^2-1)\sqrt{(E/\rho g)}]\}\sqrt{2}$ and
G = geometrical factor = $16[r^2(r^3-3Rr^2+3R^2r-R^3)]/\{R\sqrt{[2(r-R)]}\}$

which is the critical load. For safety, assemblies are rated for P/2 to P/3. Note that, unlike we assumed here, the ball and the dishes need not be the same material and could be made thick hard coated or composite. In such cases, the above criterion (5) is more involved and requires the knowledge of more parameters. We obtained (5) using Mathcad's symbolic processor. Short hand derivations are not practical here.

Once we satisfy with the basic design, we still have to make some checking on contact stresses and indentation depth. These have to be compared to the allowable elastic stresses or to the strength of the material and to the surface roughness respectively. These calculations are not discussed here.

The importance of any single parameter can be assessed by taking the partial derivative in respect to the parameter in question as equal zero or by using perturbation methods. For instance, to assess the importance of density over allowable load we can examine the partial derivative $dP / d\rho = MG[1/\rho + \rho/(2E^2)]$. Instead of going into such detail, we summarize the major design principles.

The design is more effective when we use:
- Stronger, more rigid, harder, more layered and smoother ball and dishes;
- Ball and dish radiuses to yield in higher period isolation assembly; and
- Dishes with smaller contact areas touching the equipment and support.