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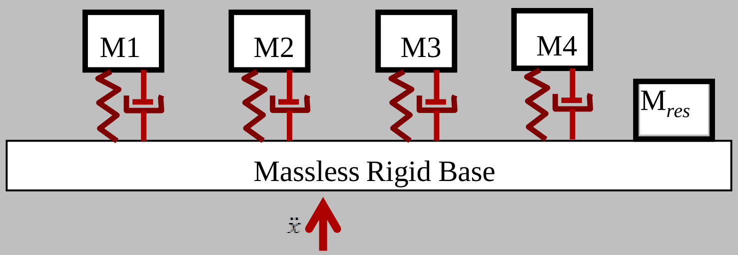
A Simpler Formulation for Effective Mass Calculated from Experimental Free Mode Shapes of a Test Article on a Fixture



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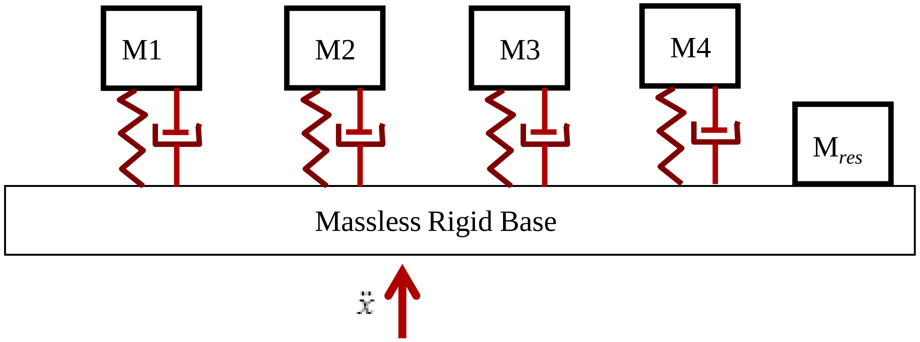
Motivation for Simpler Experimental Effective Mass

- An effective mass model is a modal model of a system mounted on a rigid base useful for calculating the system response in one direction to base input in that direction.
- It is useful for simulating dynamic loads of a payload on its bus or the energy in the system due to the base motion.
- Traditionally the effective mass modal model was derived from finite element (FE) model fixed base mode shapes, mass matrix and rigid body mode shapes.
- In cases where no FE model is available, but there is hardware, experimental effective mass would be beneficial.
- At IMAC XXXI, Mayes, et al. presented an experimental method to calculate effective mass from a free modal test of the system on a fixture. Analysis involved a 3 step process. Step 2 was complex.
- Here we present an equivalent 3 step process, but step 2 is simpler and provides much more physical insight. In certain cases it appears more robust to experimental error.

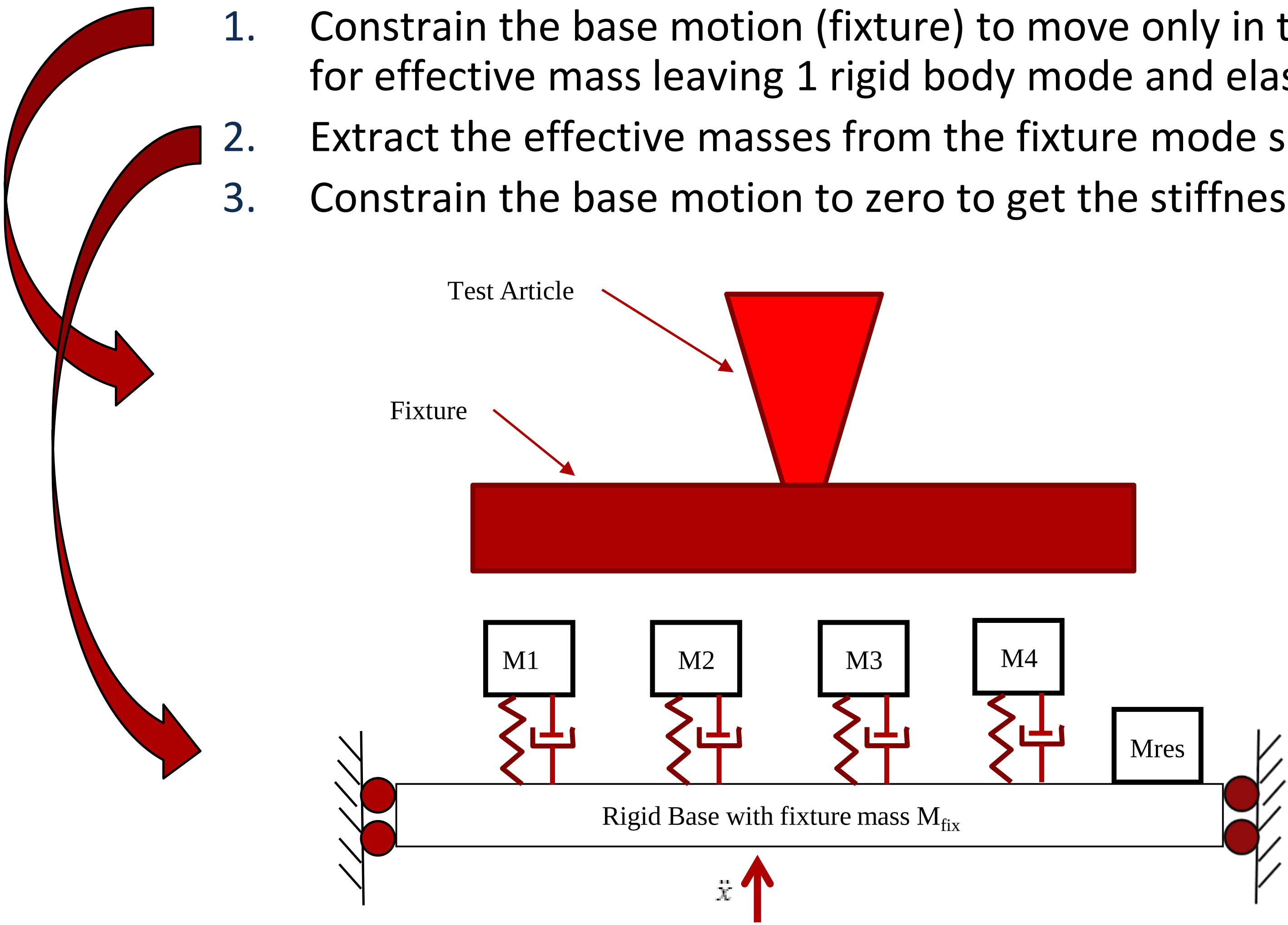
Effective Mass Modal Model

- Effective mass modal model truncated to 4 modes (below)
- The masses are scaled so that the physical force of the system on the base due to the enforced base motion is the same as the real system. Also the kinetic, potential and damping energy represents that of the real system (assumes linear system).



Analytical Steps to Obtain Effective Mass Model From Free Modal Test on Fixture

1. Constrain the base motion (fixture) to move only in the desired direction for effective mass leaving 1 rigid body mode and elastic modes.
2. Extract the effective masses from the fixture mode shapes.
3. Constrain the base motion to zero to get the stiffness and damping.



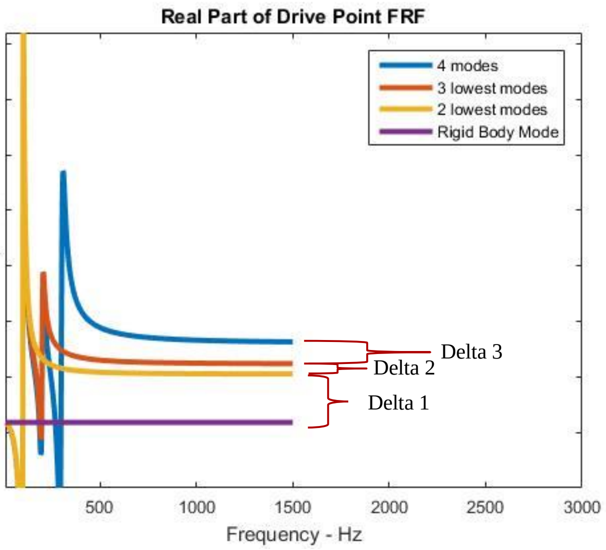
Deriving the Effective Masses from Step 2

- The modal model of the system constrained with only one rigid body mode in the direction of the desired effective mass can be used to create a drive point accelerance FRF on the fixture.
- The high frequency mass lines in this analytical FRF can be used to determine the effective mass for each mode. The FRF also provides physical insight:
  - Low response in real and imaginary part of FRF (small delta) indicate low effective mass
  - Large response in real and imaginary part (large delta) indicate high effective mass

$$H_{dp}(\omega) = \sum_{r=1}^{n} \frac{-\omega^2 \Theta_{b\_r}^2}{\omega_r^2 - \omega^2 + 2j\omega\zeta_r\omega_r}$$

$$\Theta_{b\_RB}^2 = \frac{1}{m_{fix} + m_{TA}}$$

$$m_{eff\,r} = \left(\Phi_{b\_RB}^2 + \sum_{i=1}^{r-1} \Phi_{b_i}^2\right)^{-1} - \left(\Phi_{b\_RB}^2 + \sum_{i=1}^{r} \Phi_{b_i}^2\right)^{-1}$$



Step 2 effective masses are an approximation

- If the mass of the base (or fixture) is infinite, there is no approximation (but signal to noise ratio may be poor)
- Simulations with 3 DOF system showed that if the mass of the base was more than 10 times the mass of the test article, the effective mass error was less than 0.1 % of the total mass of the test article. Previous work showed that the measured approach could have error up to 3.5% of the test article mass, so this is within that measurement error.
- The previous method used pseudo-modal participation factors that were subject to modal truncation error (errors from higher modes that are not extracted).
- This simpler drive point method only depends on the modes that are extracted, as long as the fixture motion is well approximated.

A Review of the Constraint Application (Step 1 and 3)

- In step 1 we constrain all the modes of the fixture except the rigid body mode in the direction of interest.
- In step 3 we constrain the final rigid body mode to get accurate estimates of the stiffness and damping from the fixed base modes.

$$\left[\backslash\omega_r^2\backslash - \omega^2 \mathrm{I}\right]\{q\} = \{0\}$$

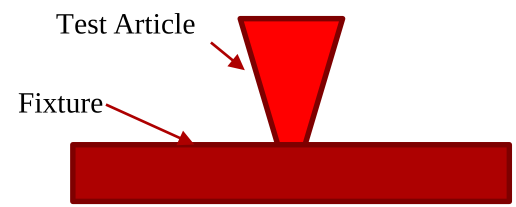
$$\{x_b\} \approx \Phi_b\{q\} \approx \Psi\{s\}$$

$$\Psi^+\Phi_b\{q\} \approx \{s\}$$

$$\Psi_{2:n}^+\Phi_b\{q\} \approx \{s_{2:n}\} = \{0\}$$

$$\{q\} = \mathrm{L}\{\eta\}$$

$$\mathrm{L} = null(\Psi_{2:n}^+\Phi_b).$$



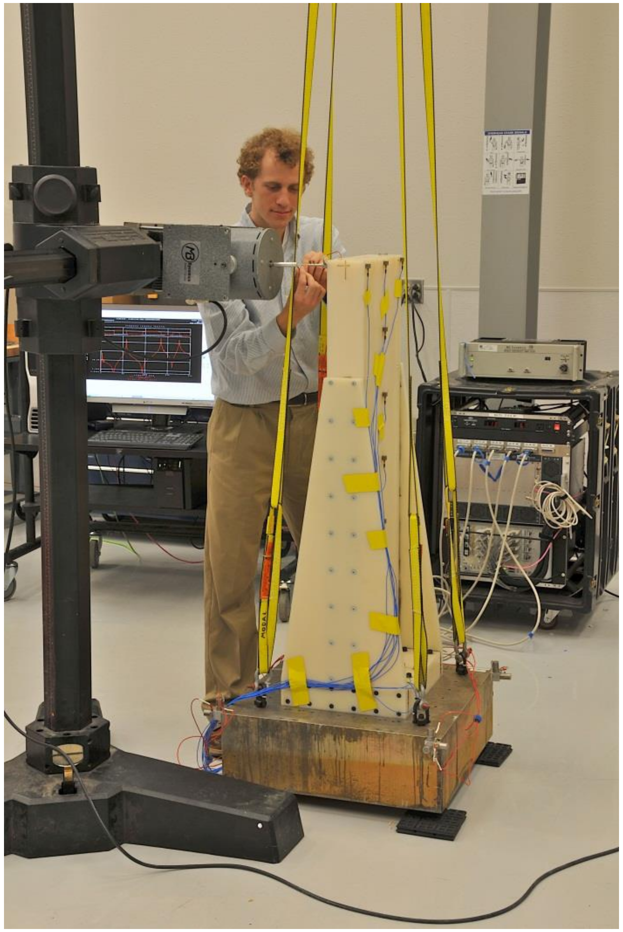
Free modes of fixture

Experimental Example 1

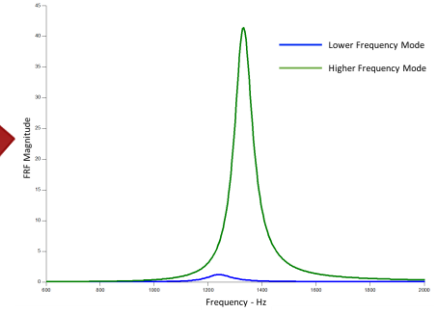
- Beam on fixture from previous work

Beam Normalized Effective Masses in Soft Bending Direction - PMPF vs New Drive Point

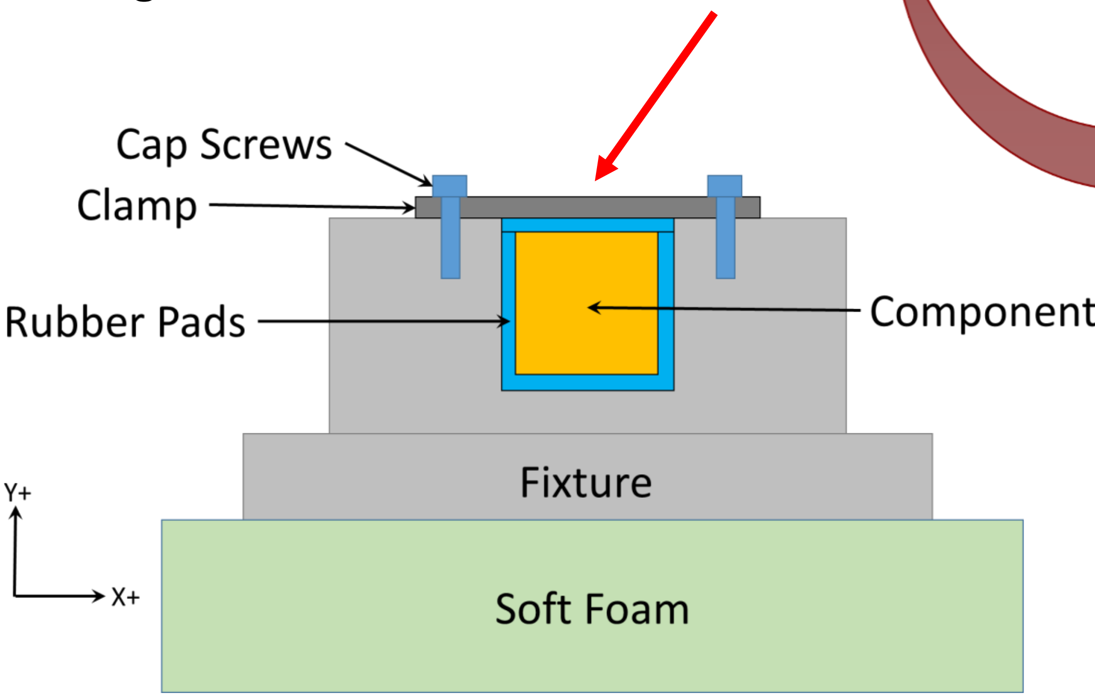
Fixed Base Test Frequency (Hz)	Effective Mass from PMPF	Effective Mass from DP method	Difference as % of Total Test Article Mass
38	0.4152	0.4141	0.1
162	0.1870	0.1871	-0.0
393	0.0882	0.0885	-0.0
702	0.0372	0.0372	0
853	0.0036	0	0.4
1028	0.0107	0.0155	-0.5
1040	0.0031	0.0320	-2.9
1199	0.0001	0.0001	0
1301	0.0273	0.0034	2.4
1344	0.0199	0.0026	1.7
Total Mass	0.792	0.780	1.5



Experimental Example 2



- Component in metal fixture
- Clamp region of fixture was not rigid so it introduced some error



Component Normalized Effective Masses - PMPF vs New Drive Point Theory

Fixed Base Frequency (Hz)	Effective Mass from PMPF	Effective Mass from DP method	Difference as % of Total Component Mass
X Direction			
397	0.001	0.001	0.0
644	0.111	0.105	-0.6
875	0.001	0.001	0.0
1227	0.388	0.155	-23.3
1292	0.593	0.826	23.2
1710	0.008	0.010	0.2
Total Mass	1.102	1.097	-0.5
Y Direction			
397	0.000	0.000	0.0
644	0.007	0.007	0.0
875	0.095	0.089	-0.6
1227	0.007	0.006	-0.1
1292	0.011	0.009	-0.2
1710	1.076	1.079	0.3
Total Mass	1.196	1.190	-0.6
Z Direction			
397	0.951	0.946	-0.5
644	0.008	0.008	0.1
875	0.000	0.000	0.0
1227	0.000	0.000	0.0
1292	0.002	0.002	0.0
1710	0.002	0.002	0.0
Total Mass	0.963	0.959	-0.5

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Conclusions

- Drive point method of calculating effective mass provides very similar results on data that are easy to analyze.
- Drive point method provides some nice physical insight from the drive point FRF in the direction of interest based simply on the amplitude of the resonances on the fixture after the first constraint.
- In one example, it appeared that the drive point method gave more reasonable answers for data that were more difficult to analyze, possibly indicating less sensitivity to experimental errors.
- Also in one example, fixture motion of the clamp which was not successfully removed by analysis appeared to distort the effective mass to unrealistically high values.