High accuracy machines on factory floors

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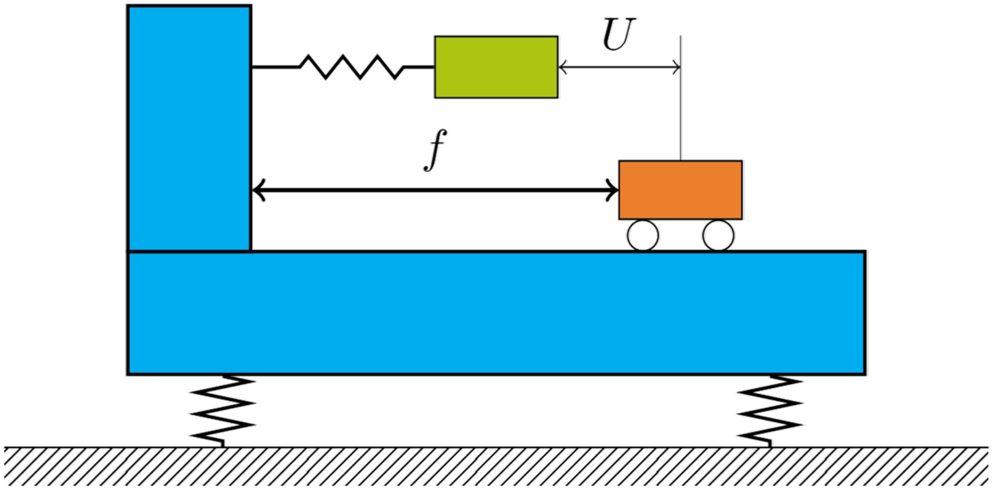
What are high accuracy machines?

- Photolithographic tools
- Healthcare machines
- Large printers

What is the problem?

- Electronic products getting smaller
- Production technique of desktop processors by Intel
  - 3 µm in 1978
  - 32 nm in 2010
- Disturbances from the floor
  - Dynamic coupling
  - Floor vibrations



Research topics

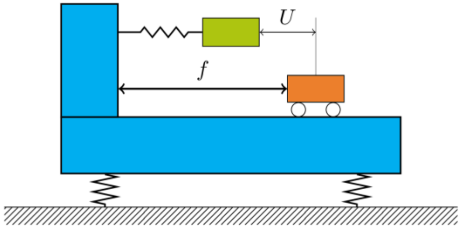
1. Investigate the dynamic behavior of factory floors and propose a method to properly predict the dynamic coupling between the machine and the floor it is placed on.

2. Develop a method to predict the new vibration level of the floor, based on the dynamic response and the free vibration level.

Presentation outline

- Introduction
- Existing methods for floor disturbances
- Frequency Based Substructuring
- Ground Vibration Transmission
- Experimental validation
- Results
- Comparison
- Conclusion and recommendations
- Questions

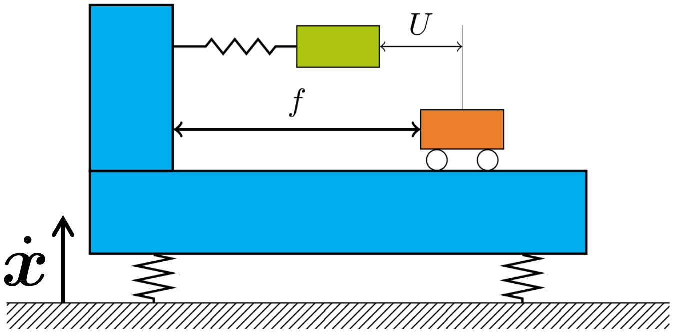
Existing methods
Dynamic coupling



Fixed

- Simple
- Only true for infinitely stiff floors

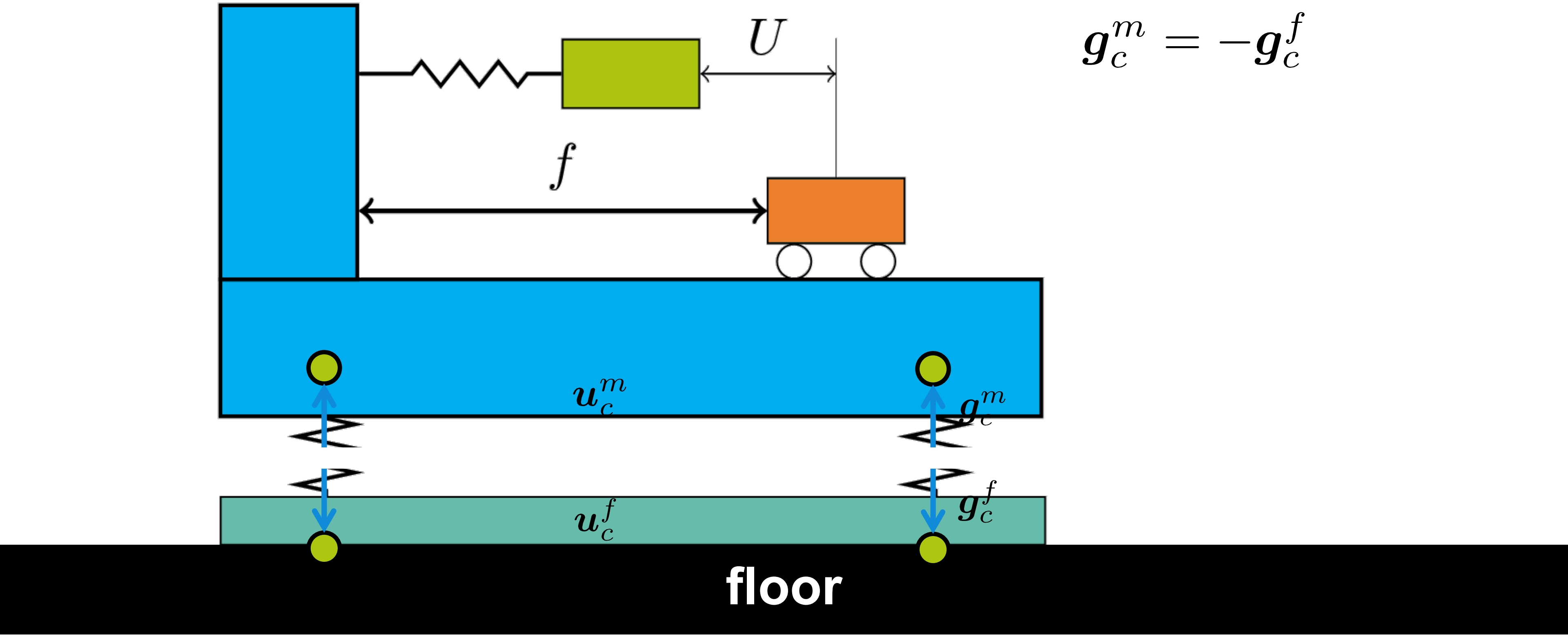
Existing methods
Floor vibrations



Directly on the mounts

- Simple
- Only true for infinitely stiff floors

Frequency Based Substructuring



Compatibility

$$\boldsymbol{u}_c^m - \boldsymbol{u}_c^f = \boldsymbol{0}$$

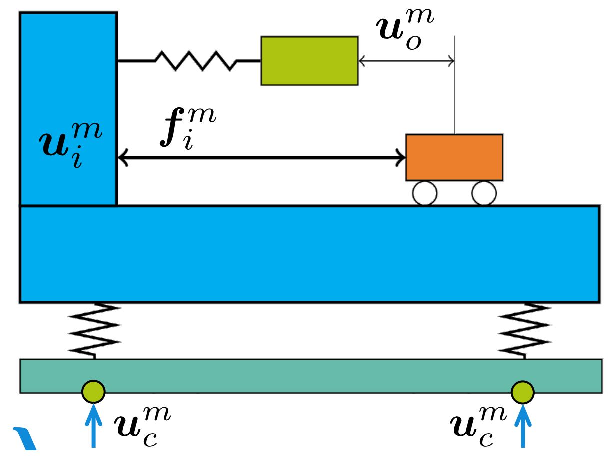
Equilibrium

$$\boldsymbol{g}_c^m = -\boldsymbol{g}_c^f$$

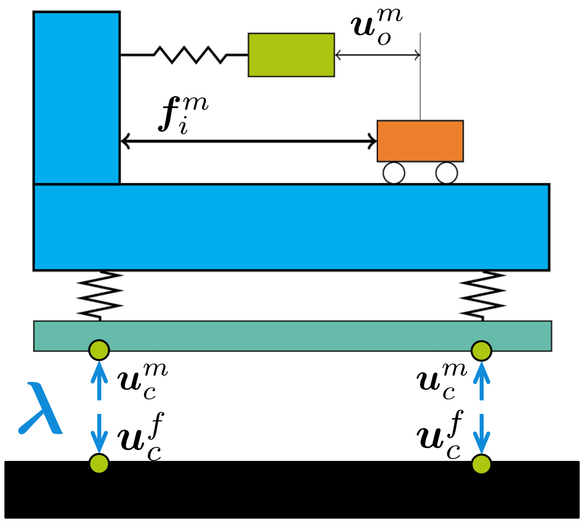
Frequency Based Substructuring

- Dynamic equilibrium of the machine:

$$\begin{bmatrix} \boldsymbol{u}_i^m \\ \boldsymbol{u}_o^m \\ \boldsymbol{u}_c^m \end{bmatrix}$$



Frequency Based Substructuring



- Summarizing:

$$\begin{bmatrix} u_i^m \\ u_o^m \\ u_c^m \\ u_c^f \end{bmatrix} = \begin{bmatrix} Y_{ii}^m & Y_{io}^m & Y_{ic}^m & 0 \\ Y_{oi}^m & Y_{oo}^m & Y_{oc}^m & 0 \\ Y_{ci}^m & Y_{co}^m & Y_{cc}^m & 0 \\ 0 & 0 & 0 & Y_{cc}^f \end{bmatrix} \begin{bmatrix} f_i^m \\ f_o^m \\ f_c^m + I\lambda \\ f_c^f - I\lambda \end{bmatrix}$$

$$\begin{bmatrix} I & -I \end{bmatrix} \begin{bmatrix} u_c^m \\ u_c^f \end{bmatrix} = 0$$

- Solving this set of equations and neglecting the applied forces on the floor yields

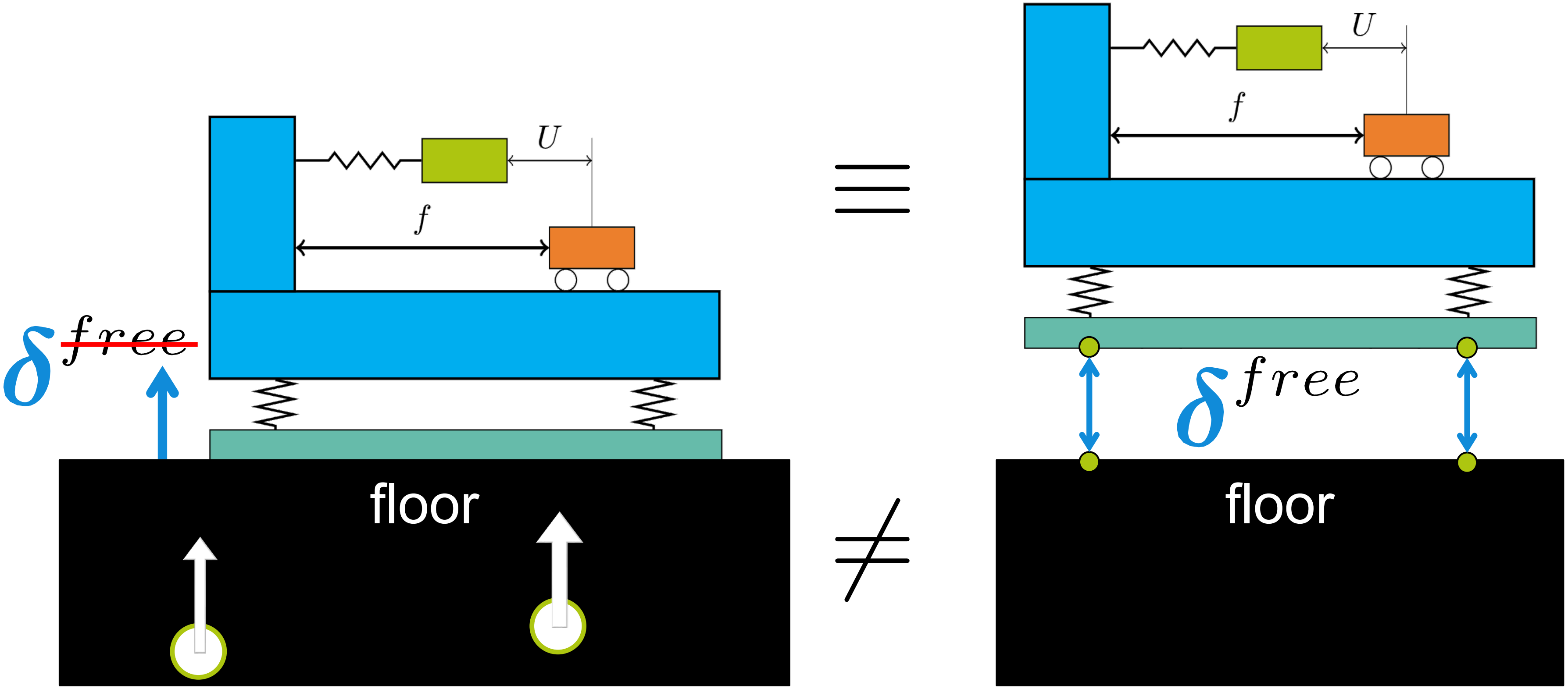
$$\begin{bmatrix} u_i^m \\ u_o^m \\ u_c^m \end{bmatrix} = Y^m f^m - Y^m \begin{bmatrix} 0 \\ 0 \\ I \end{bmatrix} \left(Y_{cc}^m + Y_{cc}^f\right)^{-1} \begin{bmatrix} Y_{ci}^m & Y_{co}^m & Y_{cc}^m \end{bmatrix} \begin{bmatrix} f_i^m \\ f_o^m \\ f_c^m \end{bmatrix}$$

Frequency Based Substructuring Dynamic flexibility

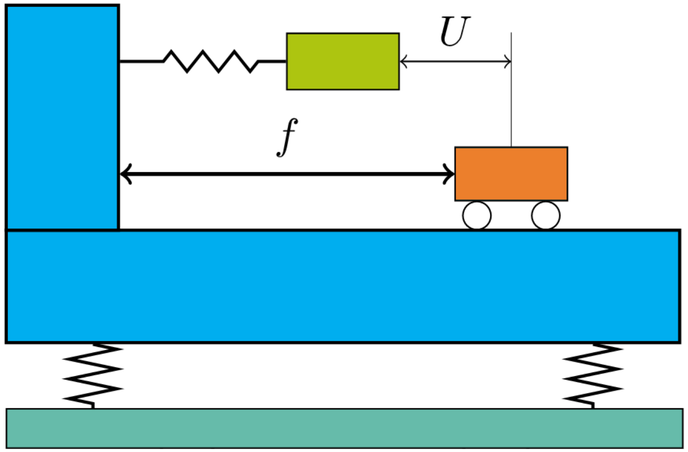
- For the machine
  - Full matrix is needed, as if it is floating free
  - Can be easily obtained from the model
- For the floor
  - Can be obtained from a model of the building
    - Difficult to model a building accurately
    - Only interface flexibility is needed
  - Solution: dynamic measurements

Ground vibration transmission

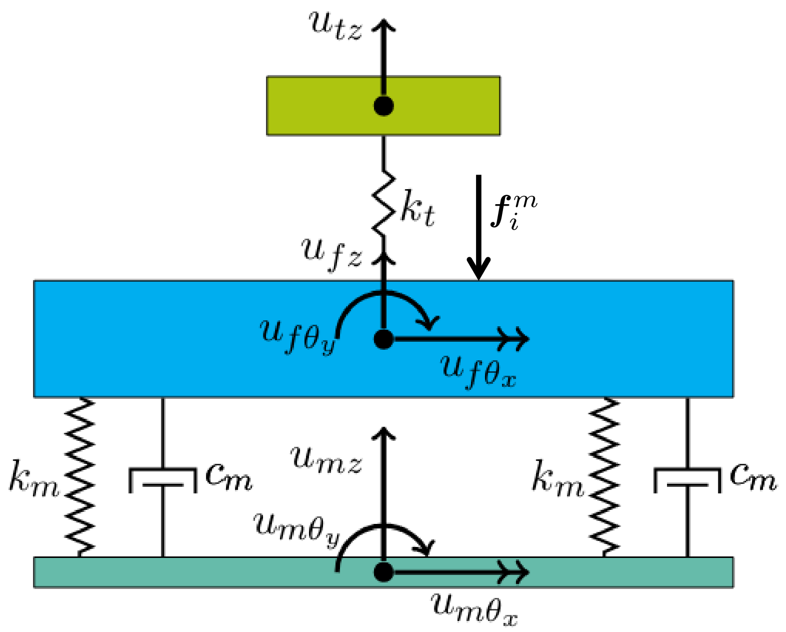
$$\boldsymbol{u}_c^m - \boldsymbol{u}_c^f = \boldsymbol{\delta}^{free}$$



Experimental validation
Test case model

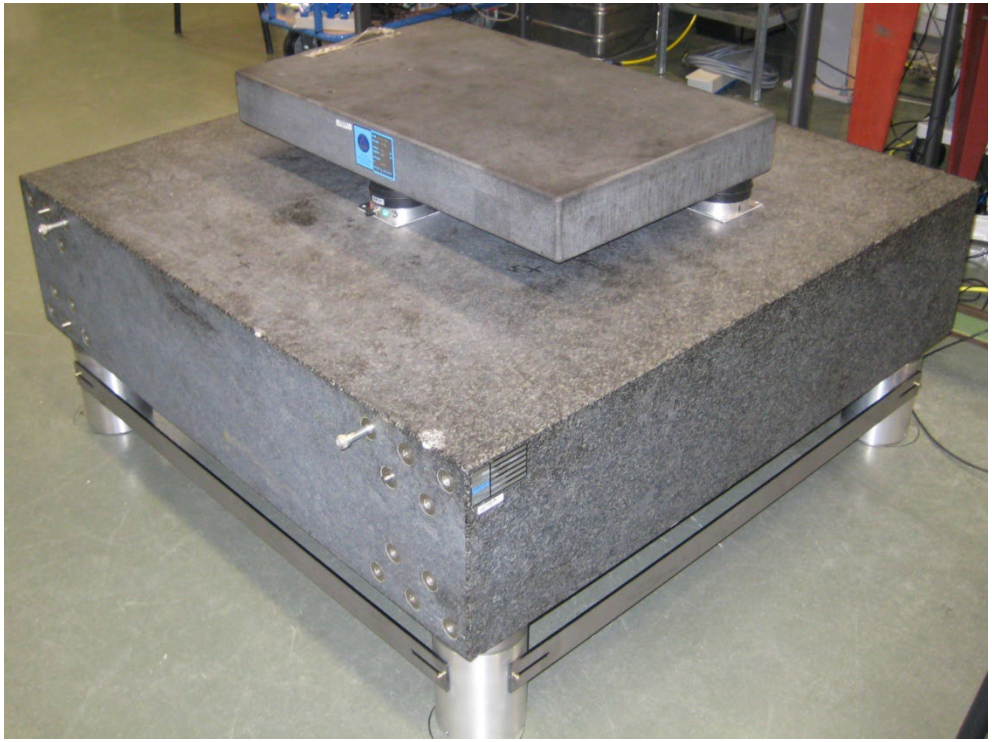


Coupling with rotations



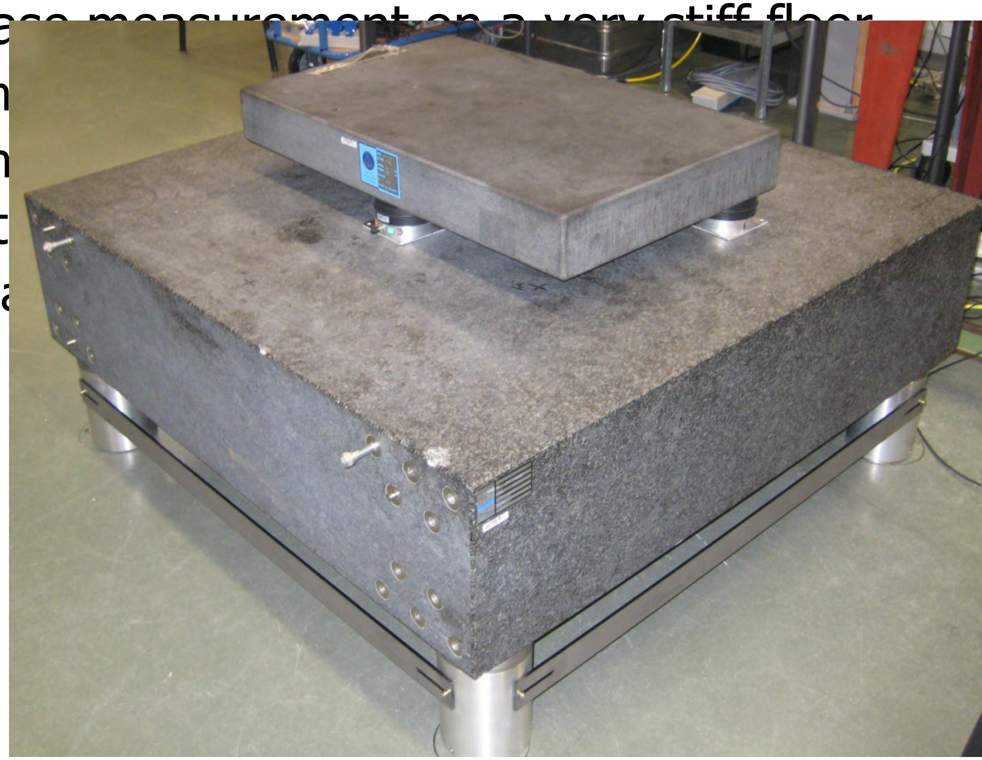
Coupling with translations

Experimental validation
Test case construction

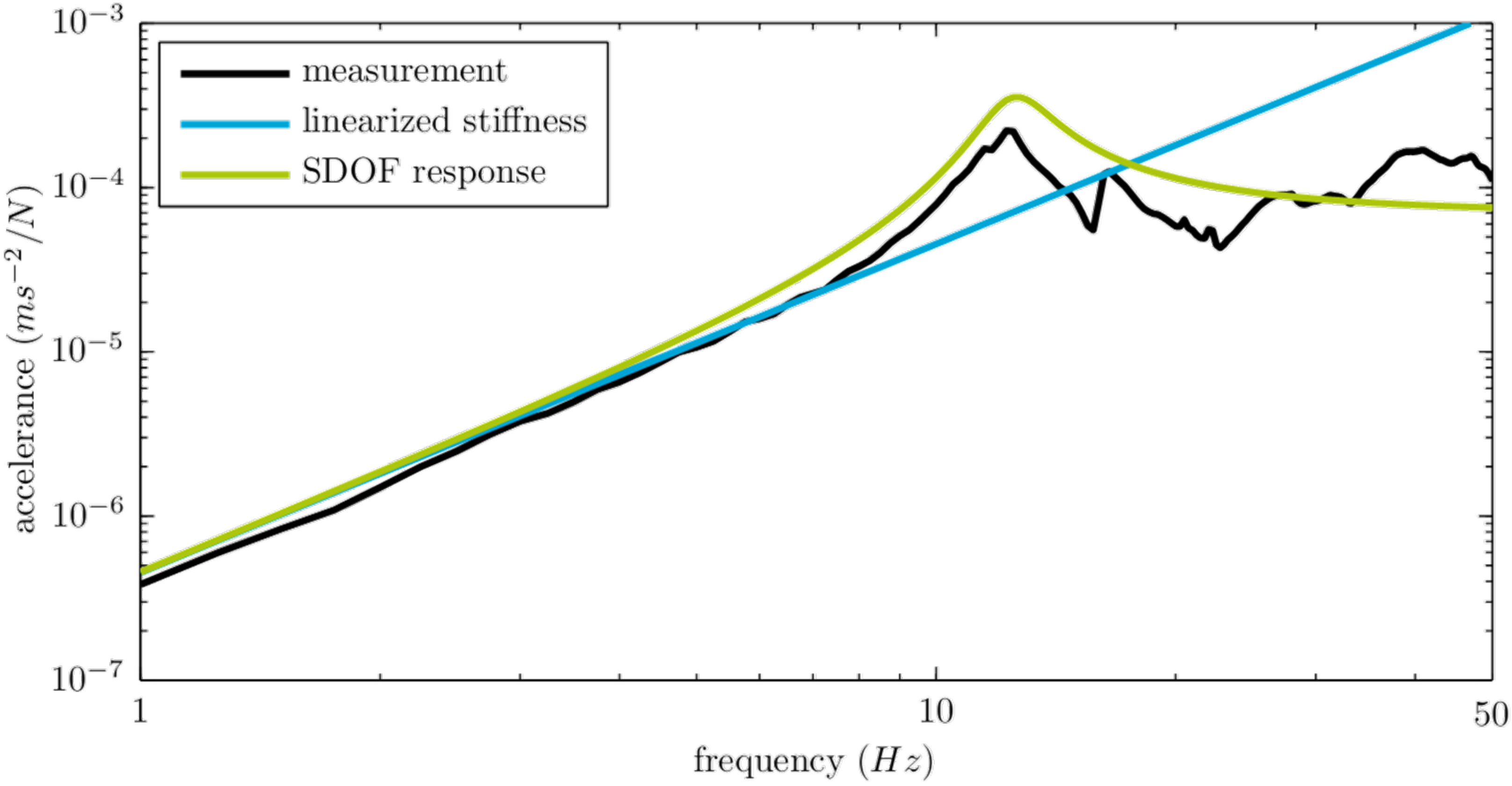


Experimental validation
Measurements

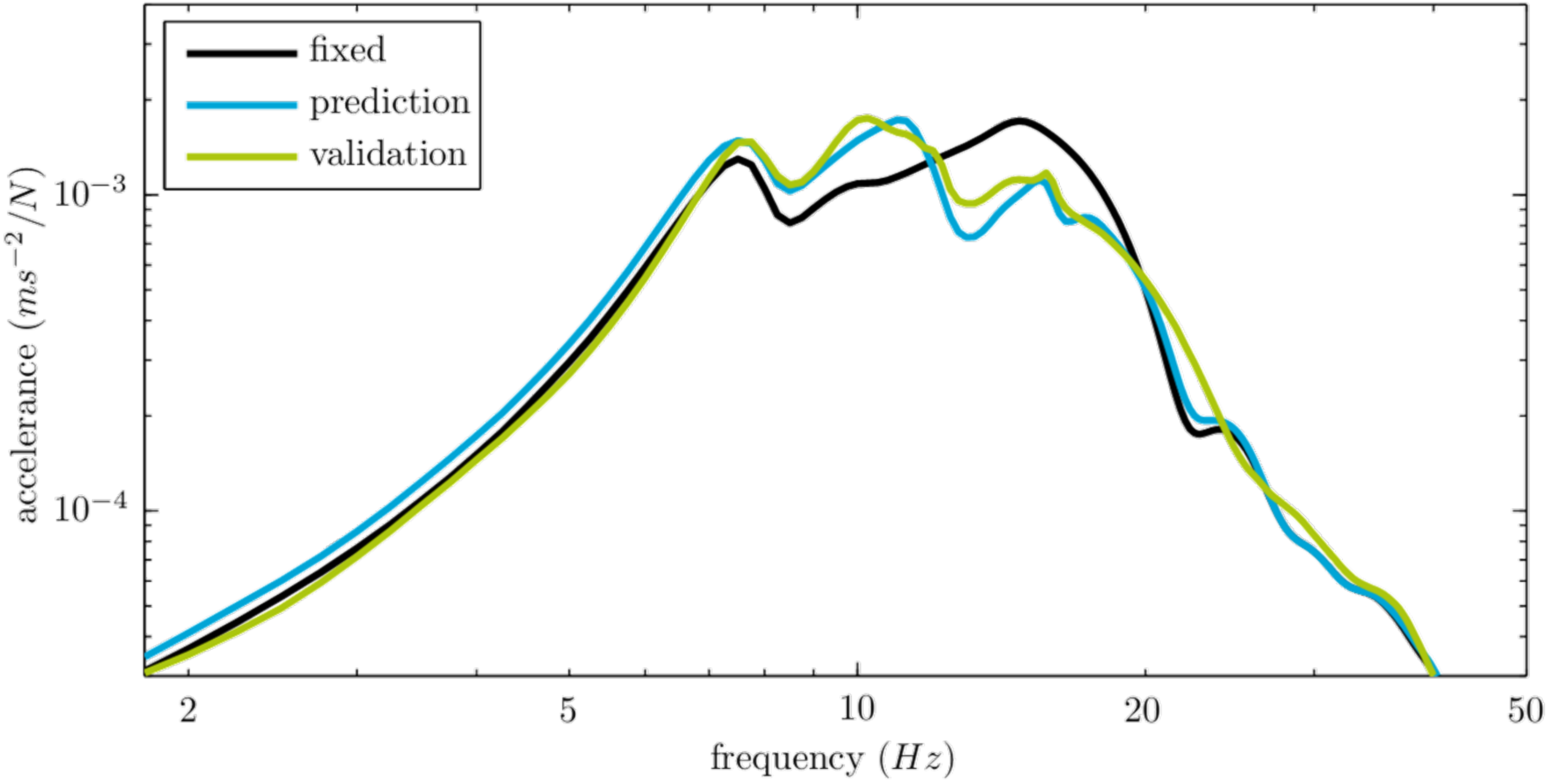
1. Floor measurement
   - Impact measurement on a flexible floor
2. Test case measurement on a very stiff floor
   - Assum
   - Obtain
3. Validat
   - Test ca



Floor measurement

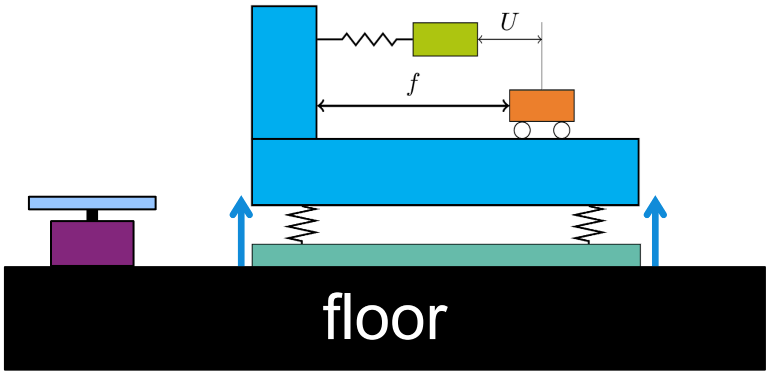


Experimental results
Coupling

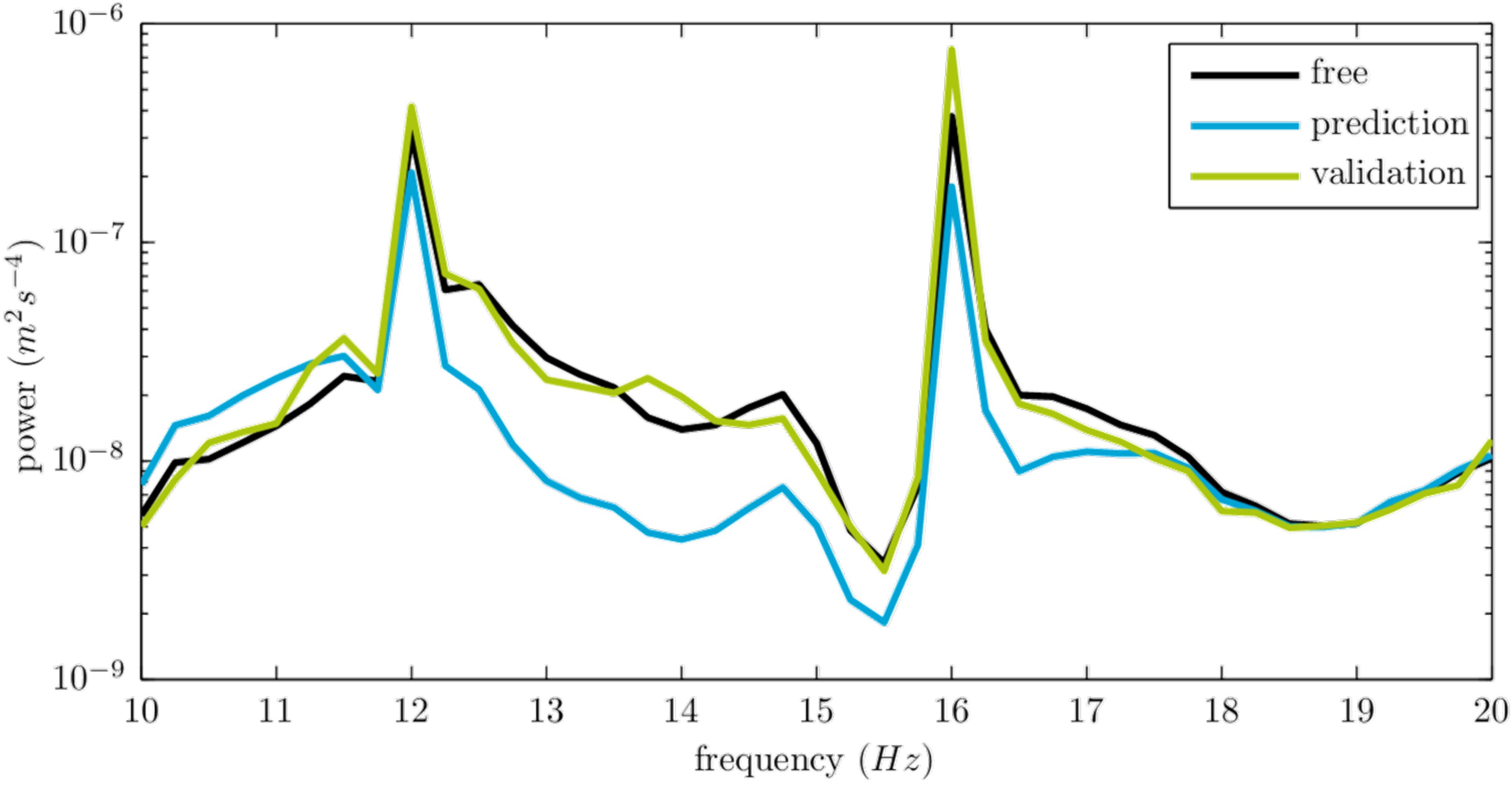


Experimental validation
Vibration measurement

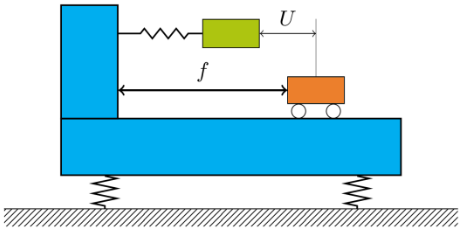
- Measure vibration level of the flexible floor with and without test case.
- Shaker with a small mass to provide equal excitations for both measurements
  - Shaker excitation: 12 and 16 Hz



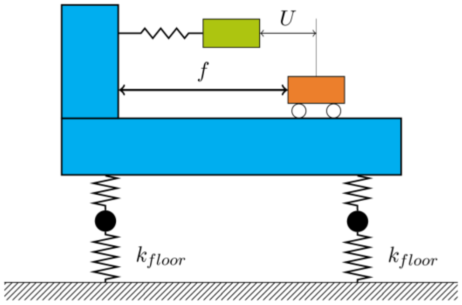
Experimental results
Ground vibration transmission



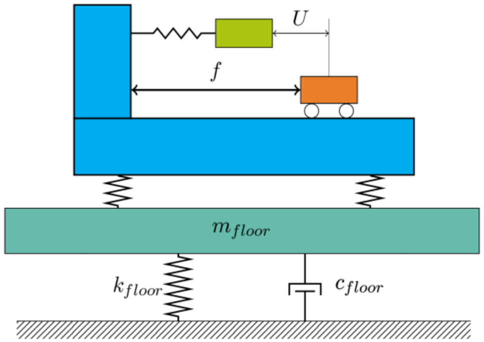
Comparison coupled response Recap



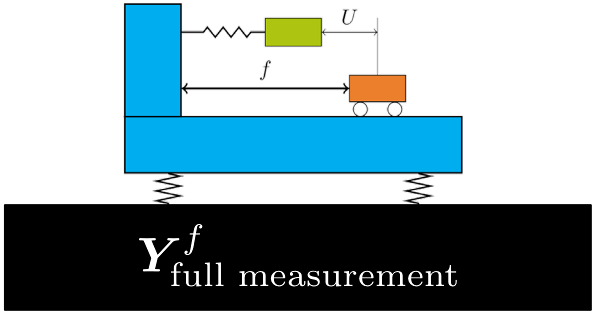
Fixed

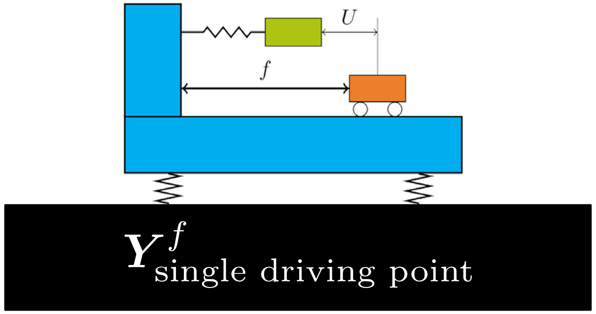


Floor stiffness

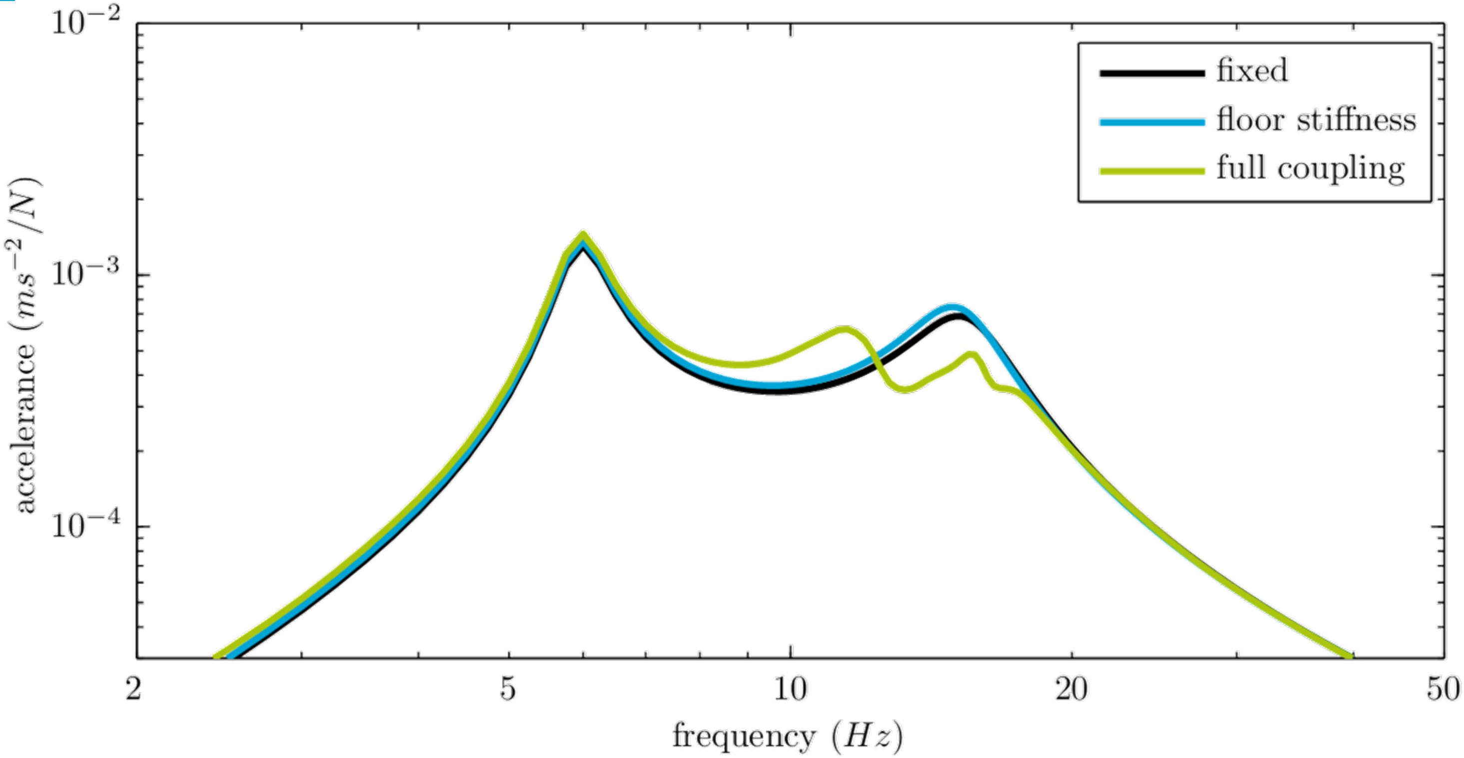


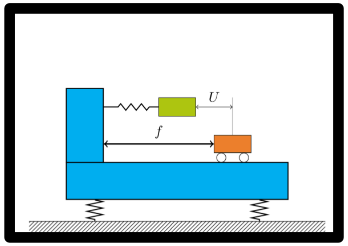
SDOF floor

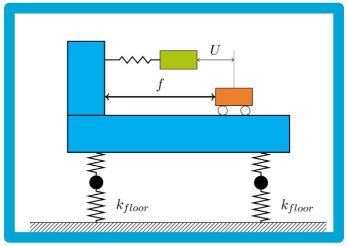


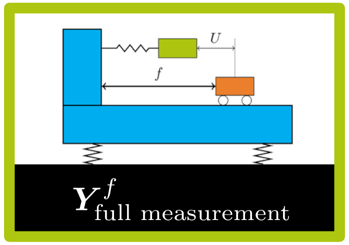


Comparison coupled response
Fixed and floor stiffness

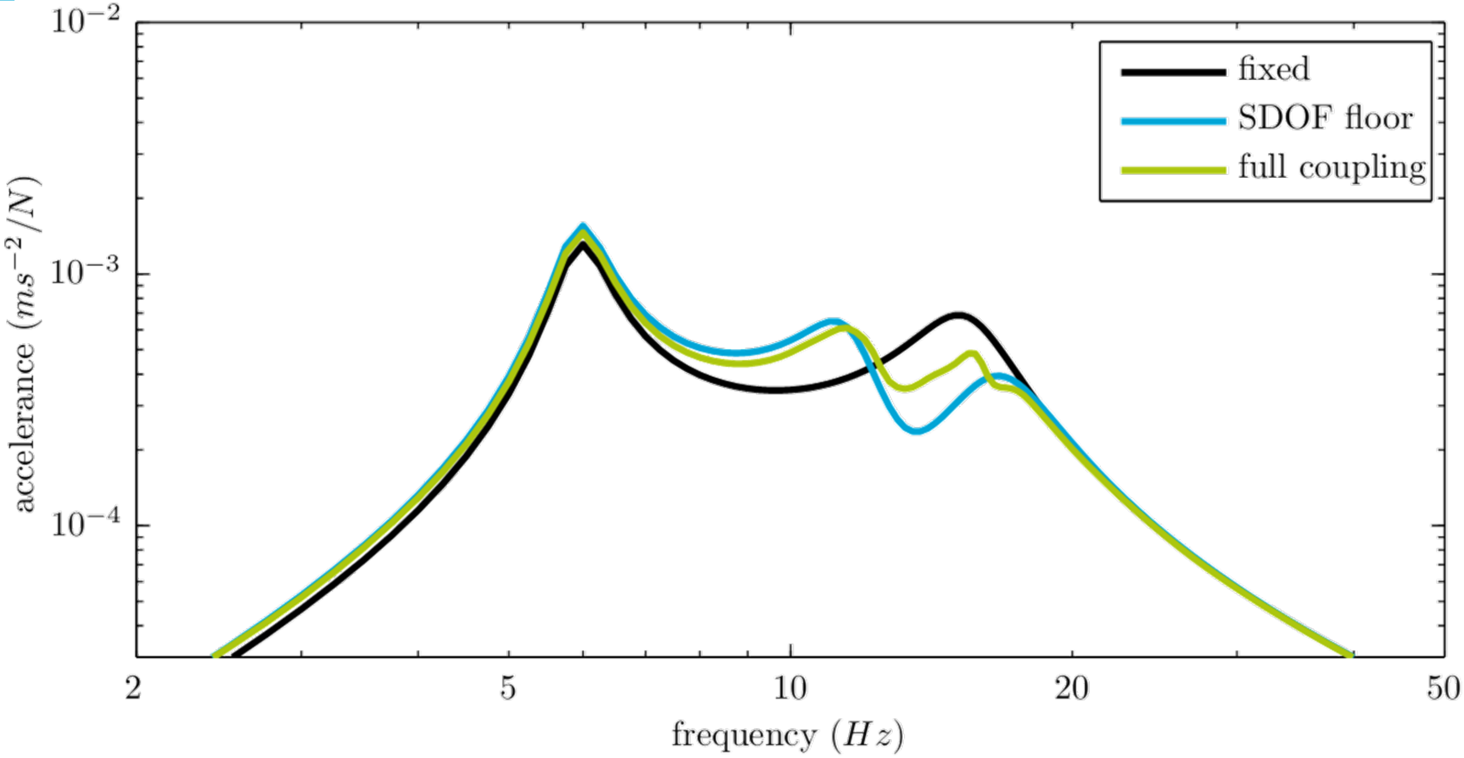


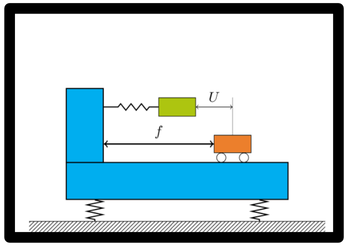


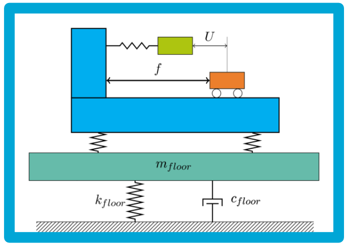


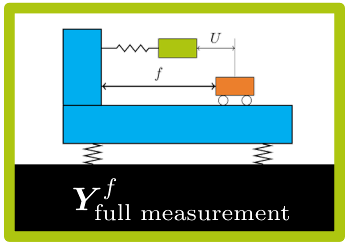


Comparison coupled response
Fixed and SDOF floor

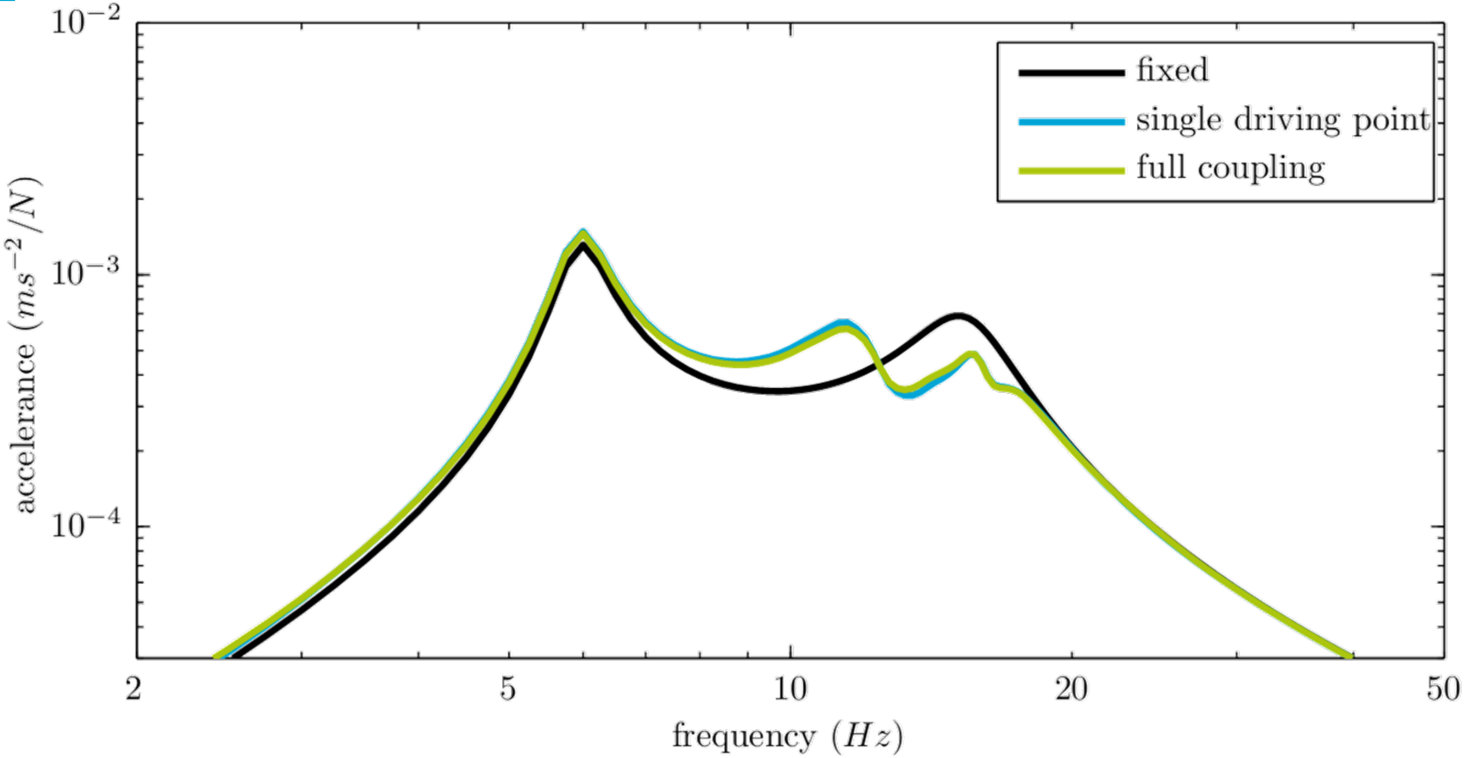


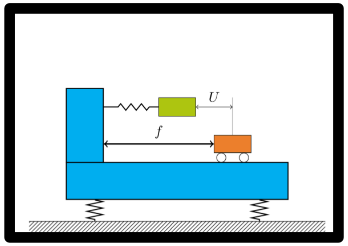


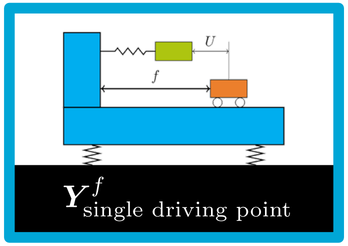


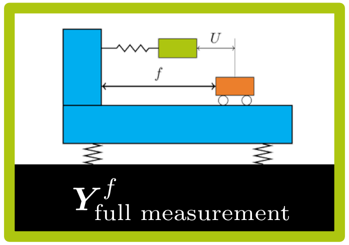


Comparison coupled response SDOF floor measurement

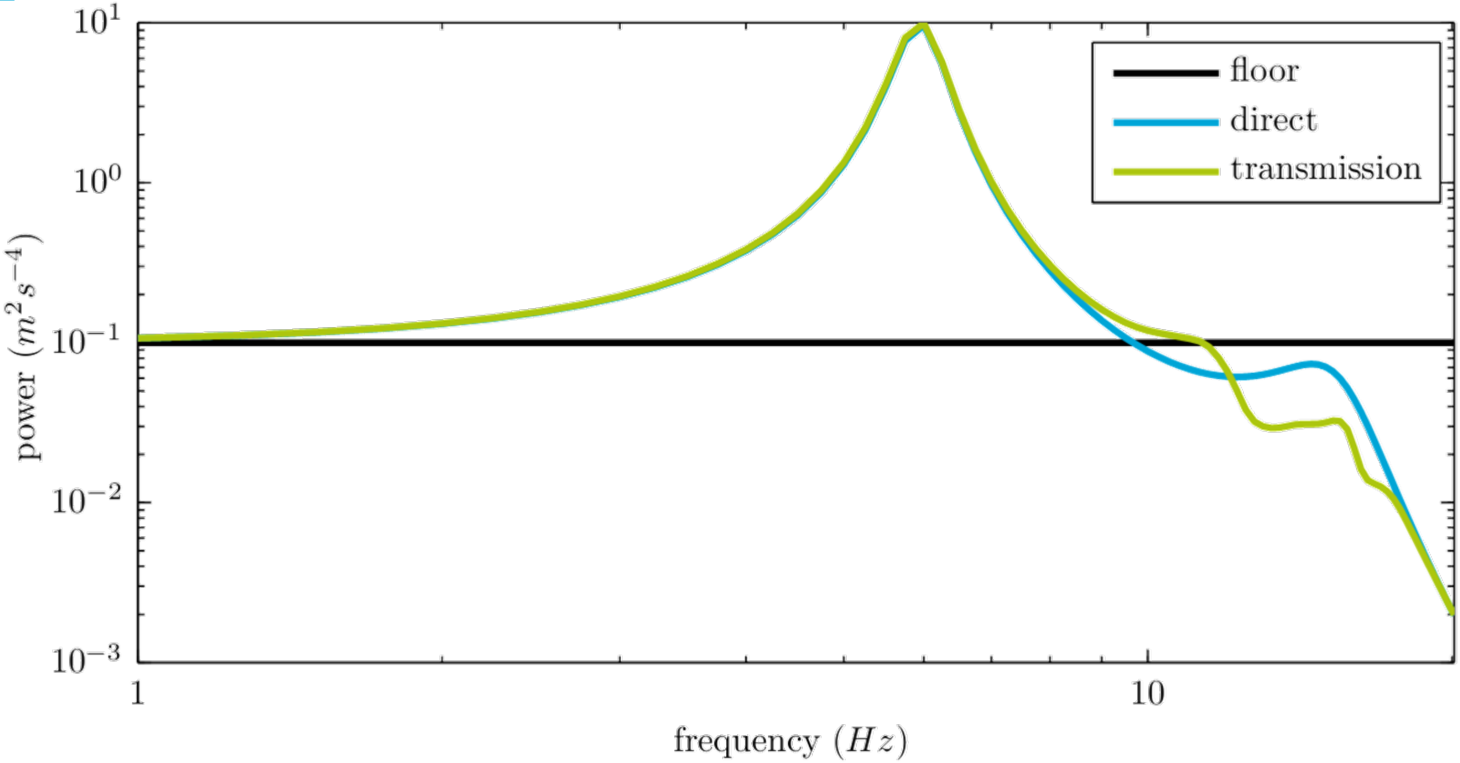


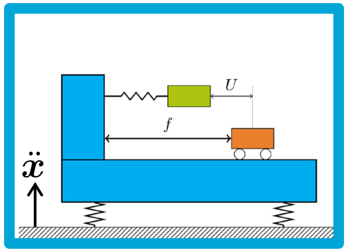


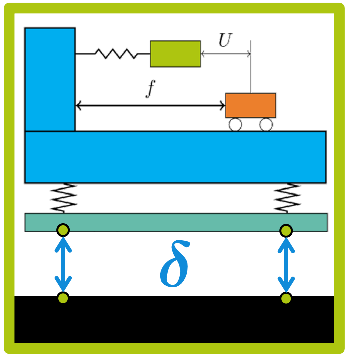




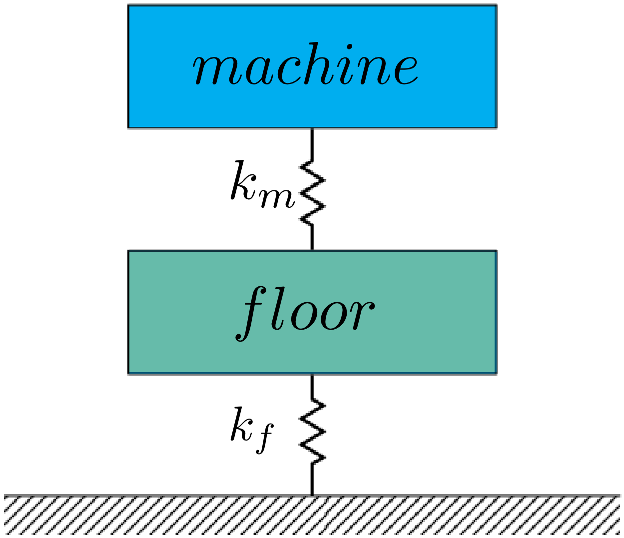
Comparison floor vibrations
Vibrations of the tool

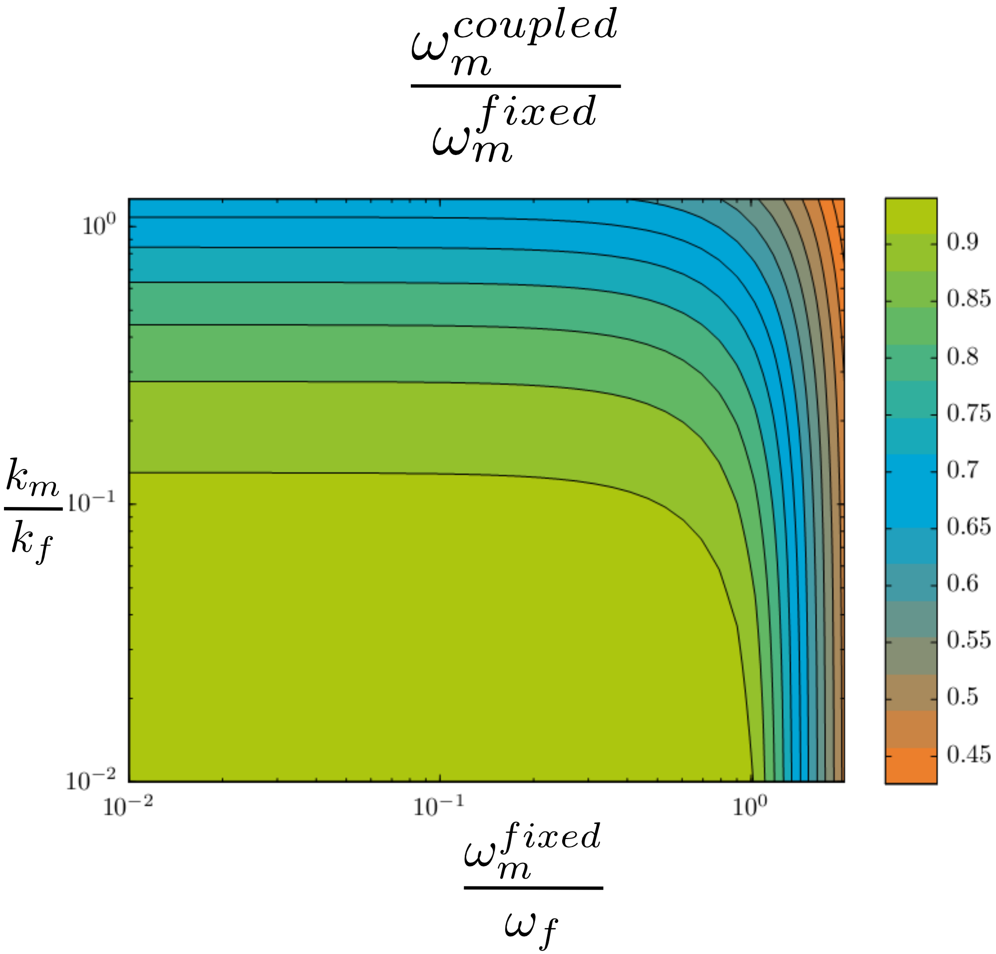






When should this method be applied?





Conclusions

- It is possible to predict the coupled response of a machine using the FBS technique and dynamic floor measurements.
- Single driving point coupling is a very good approximation
- Simple SDOF floor is a good approximation.
- Assuming a linearized floor stiffness is not always a good approximation
  - In most cases it is no better approximation than assuming an infinitely stiff floor.
- Ground vibration transmission technique was not validated.

Recommendations

- Always use the FBS method for floors with a low eigenfrequency, or when the mounting stiffness is equal to the floor stiffness.
  - Specify a floor stiffness and a fundamental frequency for the floor, to ensure proper operation of the machine.
  - Build a database with floor measurements.
  - Perform a model study with typical machinery.
- Validate ground vibration transmission technique on a much simpler test case.
  - Design a test case where one has more control over the test conditions.

Questions?