DEVELOPMENT OF A FLEXURE-BASED MODAL HAMMER

Michael F. Gomez, Ryan W. Copenhaver, T. Michael Stokes, Emma D. Betters, and Tony L. Schmitz
Department of Mechanical Engineering and Engineering Science
University of North Carolina at Charlotte, Charlotte, NC

INTRODUCTION

Impact testing is a widely used method for the determination of structural frequency response functions (FRF) [1]. Typically, an impact hammer is used to excite a structure and the corresponding response is measured. Currently, impact hammers measure forces through piezoelectric based sensors. Alternatively, force measurements can be inferred from displacement measurements using a flexure. This deconvolution of the force from the displacement response using the known structural dynamics is presented here.

WORKING PRINCIPLE

The force from a modal hammer is a short duration impact which excites a structure over a range of frequencies depending on the force profile. The flexural hammer proposed here has a single degree of freedom (SDOF) flexure which is compliant only in the direction of impact. The applied force excites the SDOF flexure and produces a vibratory response.

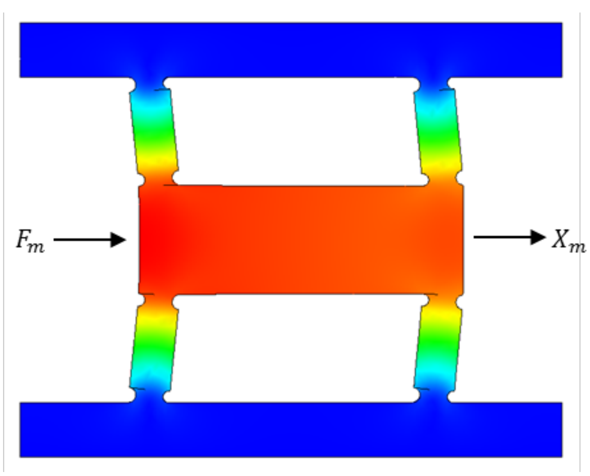

Figure 1. Working principle of the flexural hammer. An impact force, F_m, is applied to the flexure and the displacement, X_m, is measured.

The resulting flexure displacement is measured and converted to the frequency domain using the discrete Fourier transform. The frequency dependent displacement and SDOF flexure FRF are deconvolved using the inverted flexure FRF. The frequency domain impact force is obtained using Eq. 1.

$$F_m(\omega) = \left(\frac{X}{F}(\omega)\right)^{-1} \cdot X_m(\omega) \qquad (1)$$

where, $X_m(\omega)$ is the frequency domain displacement, $\left(\frac{X}{F}(\omega)\right)^{-1}$ is the inverted flexure FRF, and $F_m(\omega)$ is the frequency domain impact force. Note that the inverted flexure FRF is low pass filtered to attenuate unwanted high frequency content.

IMPACT TESTING SIMULATION

A time domain simulation was programmed in MATLAB® which calculates the displacement of a SDOF system excited by an impact force using numerical integration [1]. The impact force was modeled using a triangular profile with a magnitude of 500 N over 1 ms (Fig. 2).

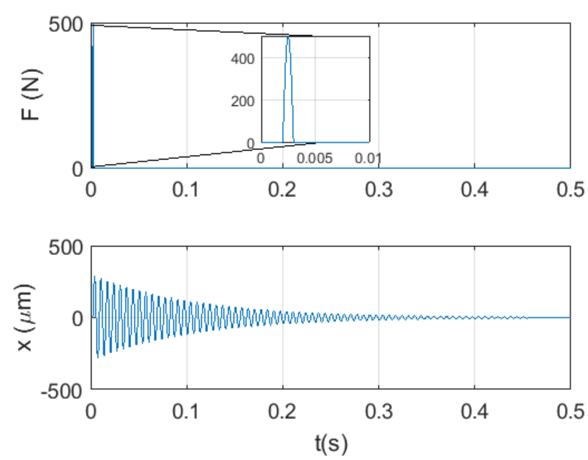

Figure 2. Time domain simulation for a SDOF flexure response (bottom) from an impact force profile (top).

Once the deconvolution is completed using Eq. 1, the frequency domain excitation force is obtained. The force content of the excitation is in good agreement with the input force up to approximately 1500 Hz; see Fig. 3. Note that the natural frequency, f_n, of the SDOF flexure shown is 200 Hz.

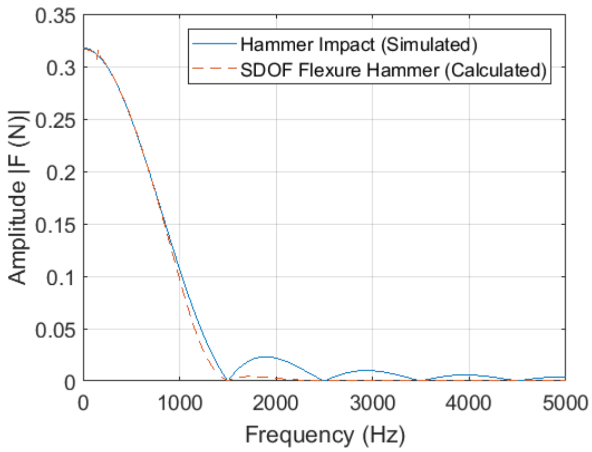

Figure 3. Comparison of the force frequency content for the simulated (input) and calculated (Eq. 1 deconvolution) impact forces.

As an additional analysis, the time domain force profiles of the simulated (input) and calculated (Eq. 1) impact forces were observed. The time response for the calculated force was obtained using the inverse Fourier transform. It is seen in Fig. 4 that the two time domain force signals are similar. The discrepancy in force magnitude is a byproduct the low pass filter applied to the inverse FRF and, therefore, the calculated force content.

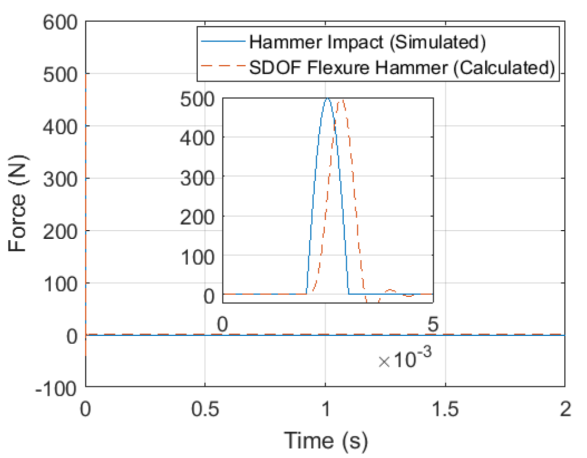

Figure 4. Time domain comparison of force profiles for the simulated (input) and calculated (Eq. 1) hammer impacts

DESIGN PARAMETER CASE STUDY

The feasibility of a flexure-modal hammer was explored through a series of simulations which were used to investigate the constraints necessary for the hammer design and development. The SDOF flexure dynamics used in the simulation are provided in Table 1.

Table 1. SDOF flexure dynamics.

f_n [Hz]	Damping ratio	Stiffness [N/m]
200.0	0.01	1.0×10^6

The first set of tests were performed to assess the effect of flexure dynamics on excitation bandwidth. During modal testing, the excitation bandwidth of the force is dependent on the structural mass and tip stiffness of the hammer. A stiff tip excites a wide frequency range with relatively low energy input. A soft tip, on the other hand, excites a lower frequency range with a higher energy input into this range [1].

To illustrate this concept, soft and stiff tip hammer impulses were simulated. The frequency domain response is displayed in Figs. 5 and 6, respectively.

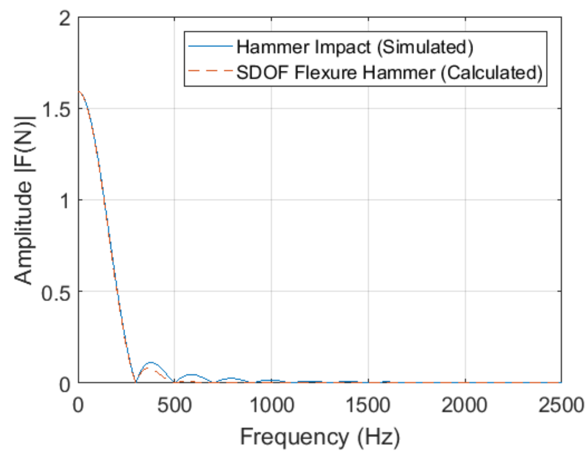

Figure 5. Frequency domain comparison of an excitation force indicative of a soft tip hammer impulse.

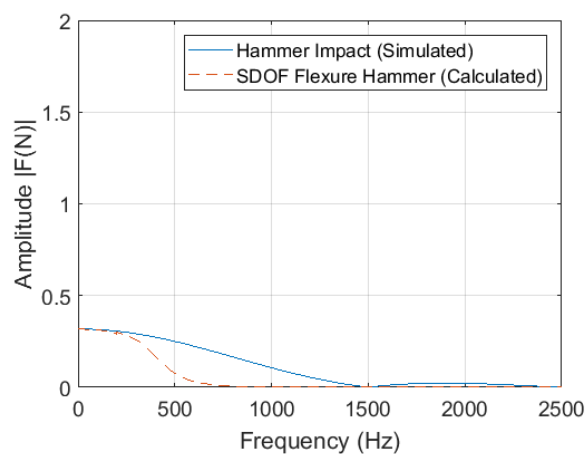

Figure 6. Frequency domain comparison of an excitation force indicative of a stiff tip hammer impulse. Note that frequency content is lost at the higher frequencies due to the low pass filter cut-off frequency.

To operate at a wide frequency range, the flexural natural frequency should correspond to the desired measurement bandwidth. Due to the low natural frequency of the flexure, force content is lost for the stiff hammer impulse, Fig. 7.

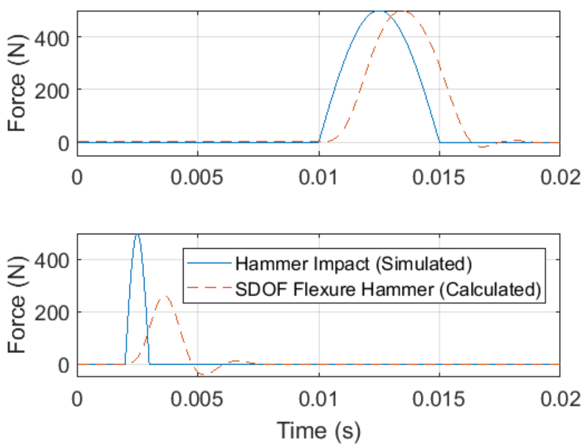

Figure 7. Time domain comparison of soft tip (top panel) and stiff tip (bottom panel) hammer impacts.

Incrementally increasing the flexure natural frequency (and low pass filter cut-off frequency) improves the ability to reproduce the impact excitation. At measurement intervals which cover a large bandwidth of excitation frequencies, a relatively high natural frequency is needed to successfully deconvolve the structural dynamics.

It is shown by Fig. 8 that low frequency excitations are less sensitive to the flexure frequency. A 4^{th} order lowpass Butterworth filter was applied to the inverse flexure FRF with a cut-off frequency equal to the two times the natural frequency.

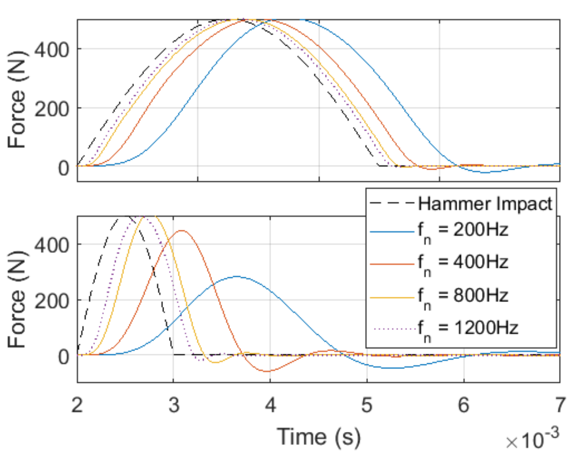

Figure 8. Time domain comparison of simulated and calculated forces at varying natural frequencies.

The effects of noise on the structural deconvolution method is demonstrated in Figs. 9 and 10. A 5% noise level was added to the displacement signal which was subsequently smoothed using a moving average filter. For the purposes of this simulation, the flexure natural frequency was 1200 Hz (based on the results presented in Fig. 8).

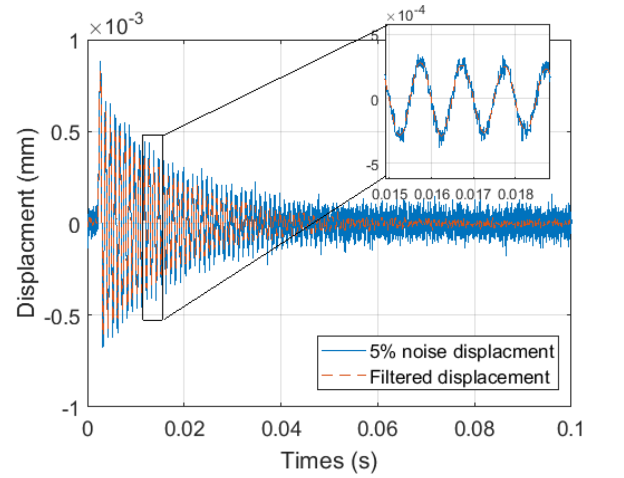

Figure 9. Time domain response of the SDOF system to a hammer impulse. A 5% noise level and a moving average filter was applied to the displacement signal.

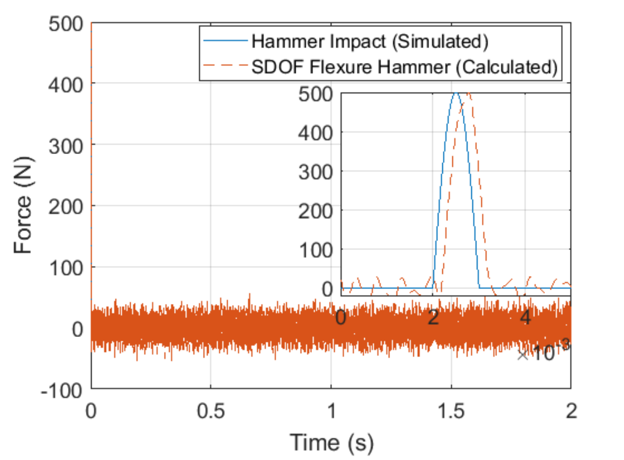

Figure 10. Time domain comparison of the simulated and calculated hammer impulse using the displacement signal shown in Fig. 9.

A low sampling frequency may also have an adverse effect on the structural deconvolution. To investigate, the simulation sampling frequency was adjusted to {5, 10, and 100) kHz. The results are shown in Fig. 11.

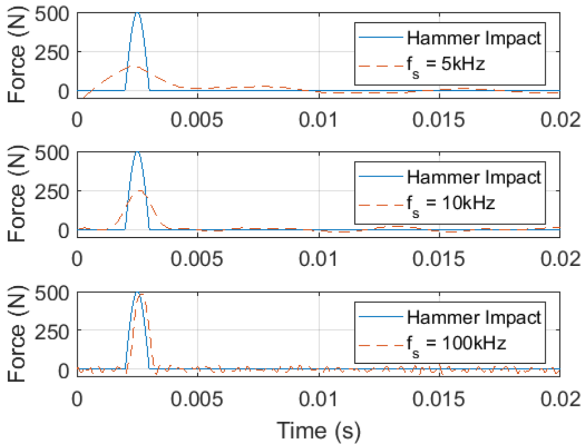

Figure 11. Time domain comparison of simulated and calculated forces with a varying sampling rate. As the sampling rate increases, the resolution and accuracy of the reproduced impact also increases.

CONCLUSIONS

It has been shown through a series of simulations that it is possible to accurately reconstruct a hammer impulse through structural deconvolution. Design constraints were developed for the use of SDOF flexure displacement measurement to reconstruct the impulse excitation force. It was shown that flexure natural frequency, signal-to-noise ratio, and sampling frequency have a considerable effect on the resulting force signal accuracy. The flexure natural frequency is an important factor which must be considered when designing and manufacturing the flexure needed for modal testing. Furthermore, a low noise vibration transducer is required to accurately reconstruct the excitation impulse. The flexure dynamics can be adjusted to excite various bandwidths depending on the measurement application.

It has been shown that knife edge [2] and curved edge sensors can be used for dynamic displacement measurements [3]. When used in combination with a SDOF flexure, this will provide a low cost alternative to traditional piezoelectric dynamic displacement devices. To continue this research, a flexure-knife edge modal hammer will be designed, constructed, and tested. A comparison with commercially available piezoelectric hammers will be performed.

ACKNOWLEDGEMENTS

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