Chapter 48
Effects of Experimental Methods on the Measurements of a Nonlinear Structure

S. Catalfamo, S.A. Smith, F. Morlock, M.R.W. Brake, P. Reuß, C.W. Schwingshackl, and W.D. Zhu

Abstract This paper continues the investigation from a paper presented at IMAC XXXIII that looked into the influence of various experimental setups on the nonlinear measurements of structures with mechanical joints. The previous study reported how the system stiffness and damping was affected by the force input method, boundary conditions and measurement techniques. However, during the stepped sine excitation experiments the parameters for the control schemes were neglected. In this paper, different control strategies, namely force and acceleration control, are used to observe how the parameters affect the measurements at different levels of excitation. The experiments are conducted on bolted beams containing a lap joint with different boundary conditions. The beams are excited by a shaker using a stepped sine signal using narrow bandwidths around three of the natural frequencies. The results show that acceleration amplitude control can produce cleaner transfer functions compared to the force amplitude control method.

Keywords Bolted joints • Nonlinear vibration • Experimental setup • Measurement effects • Testing guidelines

48.1 Introduction

Measuring the steady state response of nonlinear mechanical systems is a challenging venture since these systems tend to have multiple stable and unstable equilibria in the measured response. These difficulties originate from the fact that the measurements can be sensitive to excitation and initial conditions, and require advanced techniques not typically available in commercial software. Furthermore, recent developments have shown that small differences in the constitutive models can result in a large change in a system's response [1, 2]. In the study of mechanical joints, the lack of understanding of interfacial physics complicates the issue further [3]. In light of these known issues, the question arises: "Can the response of a nonlinear system be measured using linear measurement algorithms, and can the stiffness and damping parameters be extracted when excitation or initial condition parameters change?"

To answer this question, a candidate lap joint system termed the Brake-Reuß beam (BR beam), is proposed [4]. The beam, shown in Fig. 48.1, is designed to contain the nonlinear effects of a lap-joint in a mechanical system using a simple geometry. The joint has a strong effect on the system's transfer function (TF) [4], which is not always discernable [5], making this an ideal system to study.

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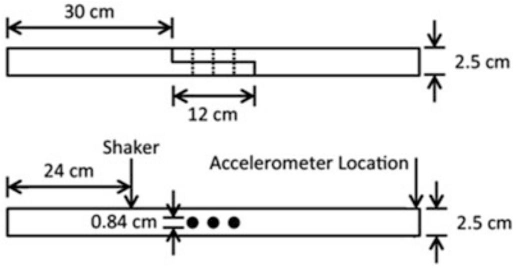
Fig. 48.1 The geometry of the Brake-Reuß beam



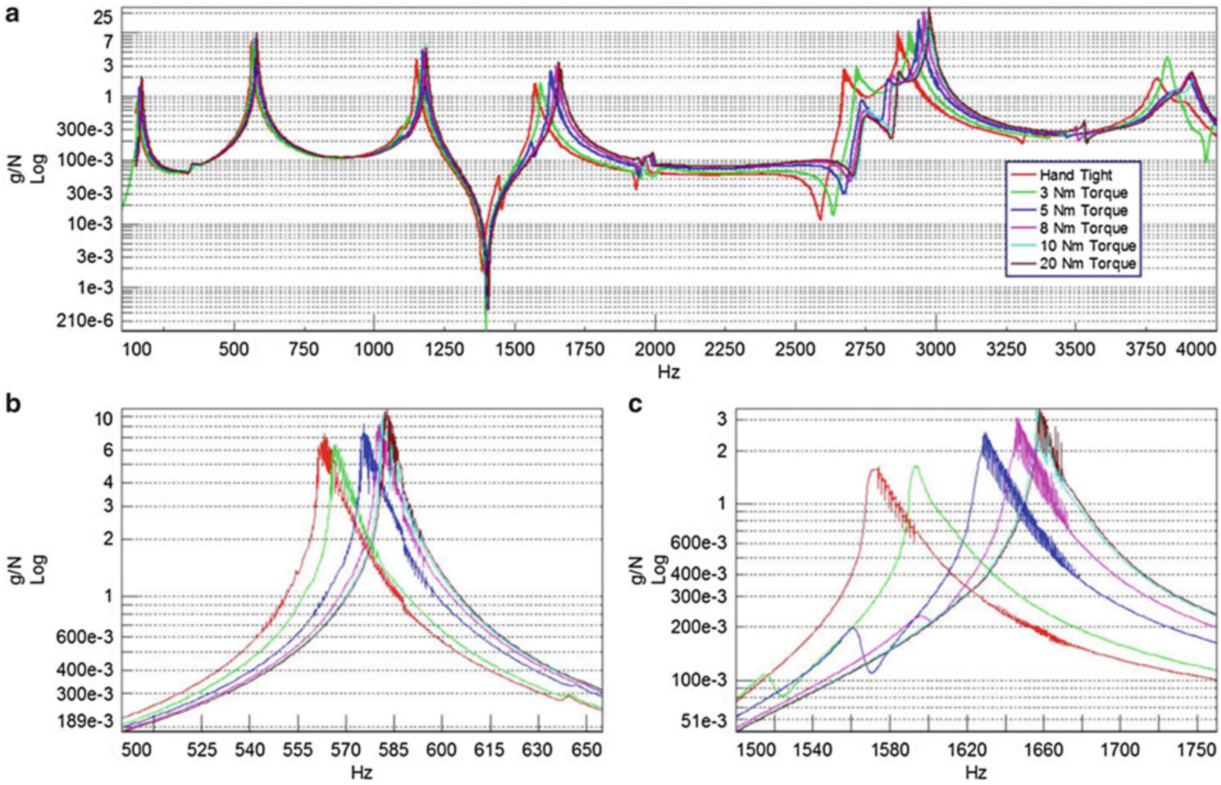


Fig. 48.2 Sample TF of the response measured using force control for (**a**) the entire frequency range, (**b**) the second natural frequency, and (**c**) the fourth natural frequency [6]

In the previous work, a "free-free" boundary condition was extensively studied [6]. A number of variables were found to have little effect on the measured frequency and damping under impact excitation, including stiffness of bungees, length of the bungees, location of the bungees, accelerometer attachment technique, mass of an impact hammer, and sensor cable orientation. A noticeable effect was seen on the torsional modes, likely due to the location or attachment technique of the bungees. Changing the size and number of accelerometers had a large effect on the frequency and damping of the system. To minimize the effects of accelerometer size and number on the response of the system, they should be eliminated or kept small and few. A shaker was then suspended to test the effects of different types of stingers: a Wire, M2 and 10-32 UNF stingers. The tests showed that the 10-32 UNF stinger had the smallest influence on the response of the system. The Wire and M2 stingers had greater influence because the torsional modes where excited. The torsional modes should not have been excited since the stringer was attached along the center of the beam's face in the vertical direction. Once boundary conditions and experimental setup was determined, the TF of the beam was measured using a shaker with a stepped sine signal and a force amplitude control algorithm. The TF of a "free-free" beam using a 1.75 N input force was not smooth, as would be expected for a control test. The issue arose from the control algorithm over correcting the divergence from the control level and not updating the TF to which it was controlling. A sample TF of the response previously measured is shown in Fig. 48.2 [6].

A continuation of the work in [6] is presented here. The only difference between the beam studied in [6] and the current system is the additional holes added for a stinger so that the torsional modes could be excited. Different control strategies for both force and acceleration amplitude control are studied. The experiments are conducted on a BR beam with either a "free-free" or "fixed-free" boundary conditions, each excited by a shaker. The results of the experimentation are the basis for the recommendations of control parameters for more reliable and repeatable measurements of a mechanical joint.

48.2 Experimental Setups

The work presented is on a "free-free" or "fixed-free" boundary condition. Regardless of the boundary condition, the beam has many common features: the interface of the joint has the same finish level, there are two accelerometers (PCB 356A01 Triaxial accelerometer) attached at the end of the beam opposite the shaker or the "fixed" boundary. Both beams are excited by a Brüel & Kjær Measurement Exciter Type 4809 which is attached to the table via bolts; the shaker is attached using the off-center holes closest to the interface via a short 10-32 UNF barrel stinger. The input force and acceleration are measured by a PCB 208C02 ICP® Force Sensor and a PCB 356A01 Triaxial Accelerometer, respectively. The accelerometer is attached to the beam on the surface opposite the force sensor.

The "free-free" boundary condition is implemented by hanging the beams using 1.2 m of 50 lb fishing line at the ends of the beam approximately 5 cm from the ends of the beam, as shown in Fig. 48.3a. The accelerometers are attached to the end of the beam furthest from the shaker. The "fixed-free" boundary is implemented by epoxying one end of the beam to a $0.127 \times 0.127 \times 0.1524$ m, 20 kg steel block. The steel block is then clamped to the table and the free end of the beam left is unsupported. The shaker is attached using the off-center hole closest to the interface, opposite the steel block, shown in Fig. 48.3b.

The rigidness of the "fixed" boundary is tested by sending a stepped-sine signal ranging from 584.5 to 585.5 Hz through the half-beam with accelerometers (PCB 356A01) attached on the beam near the block and one on the block near the other accelerometer, as shown in Fig. 48.4. The acceleration of the beam compared to the acceleration of the block at 15 and 25 g acceleration input is shown in Fig. 48.5. The results suggest that the boundary is not a true fixed boundary as there is high acceleration on the beam near the block. This high acceleration tells us that the connection to the block behaves more like a pinned joint with translational and rotational springs, and any comparison to a model must take this into account.

The "free-free" boundary condition is used in Sect. 48.3 for the determination of the control parameters. The "fixed-free" is used in Sect. 48.4 to determine if repeatable results can be received using the parameters from Sect. 48.3.

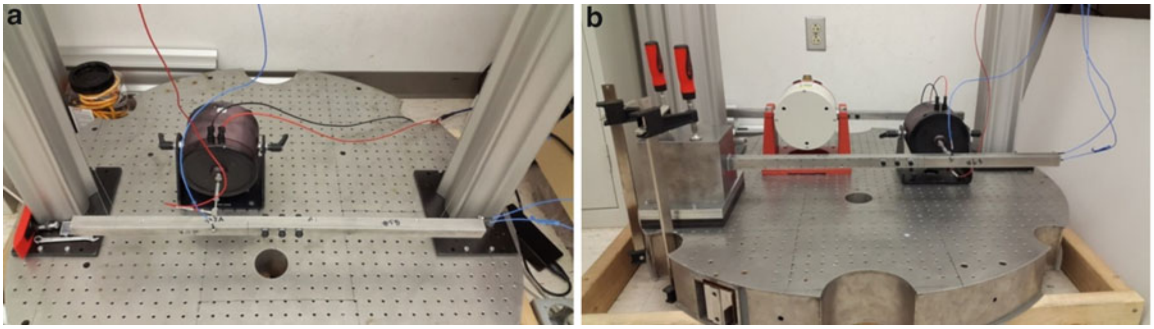


Fig. 48.3 (**a**) "Free-Free" and (**b**) "Fixed-Free" boundary conditions for the BR beam

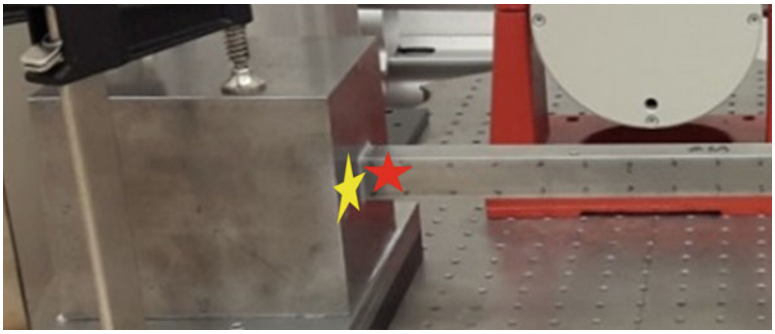


Fig. 48.4 Locations of the accelerometers for testing the rigidness of the "fixed" boundary, the *yellow star* is the location on block, and *red* the location on the beam

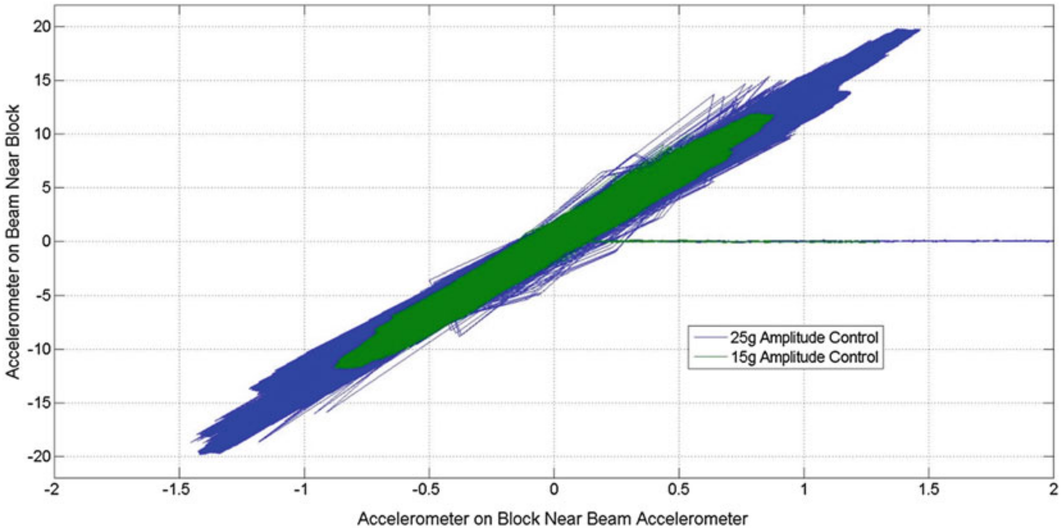


Fig. 48.5 Acceleration on the beam vs. acceleration on the block to test the rigidness of the "fixed" boundary

48.3 Control Parameter

In this section the control parameters used in LMS Test.Lab are studied to reduce/remove the saw tooth effect seen in the previous study [6]. LMS Test.Lab 15A MIMO Sweep & Stepped Sine Testing has five main parameters that affect the measured data. The first parameter is the Confidence in Measured System Frequency Response Function (FRF). Before each test a white noise signal is passed to the system and a FRF of the sensors and voltage output is created. This is what the control algorithm uses to control the output voltage. When the confidence is set to high, the algorithm assumes that the system FRF is correct for all frequencies and output amplitudes; when set to low, the algorithm does a quasi-closed loop control in which it uses the previous measurement as the starting point for controlling. In the results that follow, the low confidence parameter is always used since the nonlinear behavior in the measurements strongly influence the FRF used to control the excitation. Another parameter is the Error Correction Factor (ECF). This factor determines how much the algorithm corrects the divergence from the control band in one frequency step. When this factor is set high, a saw tooth effect may be seen in the input spectrum, resulting in a non-smooth TF. When the factor is set to low, the algorithm may not correct the divergence from the control level enough in a step, resulting in responses that may be outside the control bands and responses not controlled at the desired level.

The third parameter studied is the number of delay cycles. This is the number of cycles that the system will hold at a frequency before it starts taking a measurement; a high number would ensure that the results reach steady state, but this increases the amount of time needed to run the test. Setting this value too low could result in poor estimation of the TF since the response may not be at steady state. The fourth parameter is the number of hold cycles, which is the number of cycles that the algorithm controls at a given frequency before taking a measurement. A high number of cycles would ensure that the steady state response has less aliasing due to more averaging, but this increases the amount of time needed to run the test. Setting this value to low could result in poor estimation of the TF due to aliasing caused by the acquisition system's sampling frequency. The last parameter is the step size which determines the resolution of the TF. A large step-size may result in a large change in amplitude which is hard for the control algorithm to correctly predict, and a small step gives better frequency resolution but requires an increased amount of time needed to run an experiment.

Each of these parameters are listed below in Table 48.1. The parameters used for the stepped sine testing in the previous 2014 study [6] are given in the first column. These parameters were the default in LMS and no attempt was made to find the optimal settings. The second column is the combination of parameters that were used at the onset of this testing. The only two parameters varied during these tests are the ECF and number of hold cycles. All of the tests were run with the confidence parameter set to low, the number of delay cycles at 30, and a 0.05 Hz step size. The third column shows the recommended settings based on the results presented later in this Section.

The measurements were taken from the "free-free" boundary conditions with a 10 Nm torque applied to the bolts. Utilizing a 5 N force amplitude control, different values of the ECF is compared using a stepped-sine test from 570–580 to 1176–1184 Hz with 40 hold cycles. The results shown in Fig. 48.6 compare the measurements either stepping the signal up

Table 48.1 Control parameters used in control study

Control parameters	2014	2015	Optimal
Confidence in measured system FRF	High	Low	Low
Error correction factor	100 %	Vary	60 %
Number of delay cycles	1	30	30
Number of hold cycles	15	Vary	40
Step size	0.1 Hz	0.05 Hz	0.05 Hz

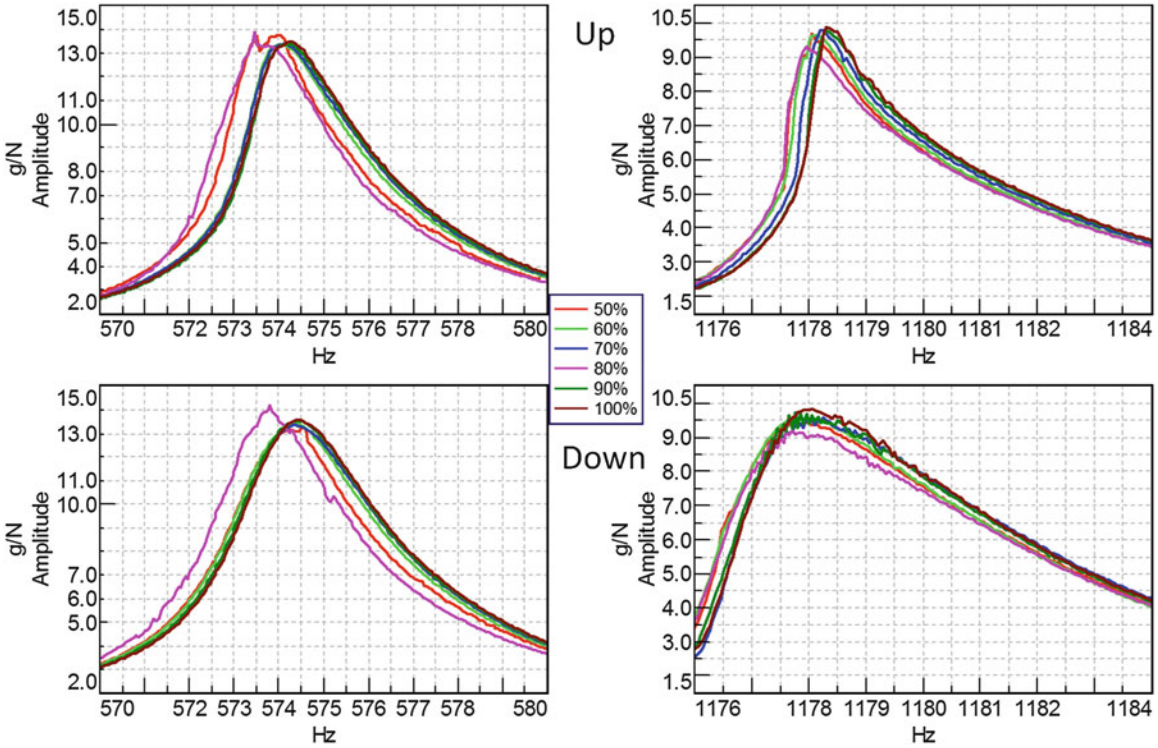


Fig. 48.6 FRFs of 5 N force control to locate optimal ECF; (*top row*) sweep up, (*bottom row*) sweep down

(top row) or down (bottom row) through the frequency ranges defined. An ECF of 60 % is the best balance of speed and accuracy for the control algorithm (these test took approximately 5 min). When the value is higher than 60 % the TF starts to get a saw tooth look; while below 60 % resulted in the algorithm not correcting the error in the amplitude towards the desired level.

Once the optimal ECF was determined the number of hold cycles using the same parameters was tested, shown in Fig. 48.7. The test was run with 5, 10, 20, 40, and 60 hold cycles. From Fig. 48.7 it is seen that the 40 and 60 hold cycles produced the smoothest TFs. Forty hold cycles though is better for testing because increasing to 60 cycles nearly doubled the amount of time a test took.

The same tests were run using 10 g acceleration amplitude control; the results are shown in Figs. 48.8 and 48.9. The parameter tests for both force amplitude and acceleration amplitude control show that an ECF of 60 % and 40 hold cycles are the optimal settings, and are listed in Table 48.1. Figures 48.6, 48.7, 48.8, and 48.9 show that the force control has more of a saw tooth response than the acceleration control. The effect could be from how fast the force amplitude drops at resonance, which requires the control to quickly put out more voltage to keep the same force level. While in acceleration control the amplitude increases quickly, however the control can more easily decrease the voltage which reduces the amount of saw tooth like effects in the signals.

The TF and time signals of the system using the parameters from the previous and the optimal parameters are compared under a 10 g acceleration amplitude control in Fig. 48.10. The comparison of the TFs (top row) shows that the optimal parameters removed the saw tooth effect seen in the previous study. As a result of using the optimal parameters the amount of time (bottom row) required to run a test increases; however, the acceleration was controlled to the level specified very well.

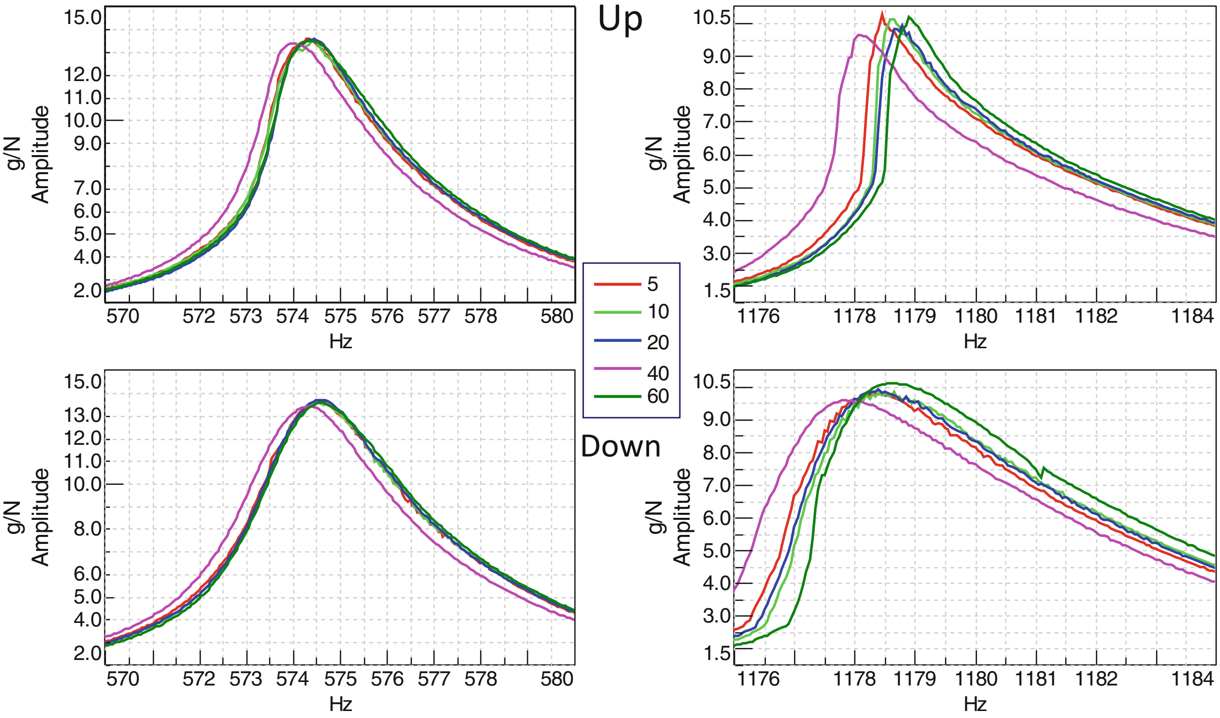


Fig. 48.7 FRFs of 5 N force control to locate optimal number of hold cycles; (*top row*) sweep up, (*bottom row*) sweep down

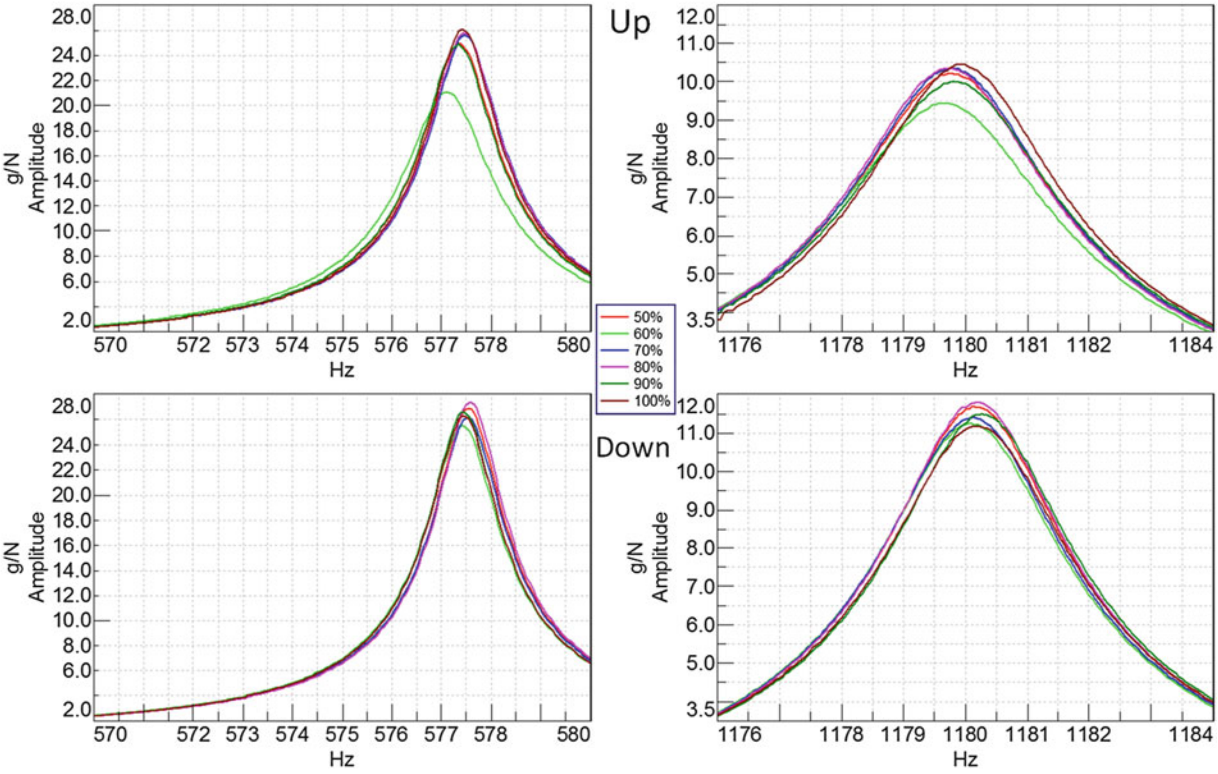


Fig. 48.8 FRFs of 10 g acceleration control to locate optimal ECF; (*top row*) sweep up, (*bottom row*) sweep down

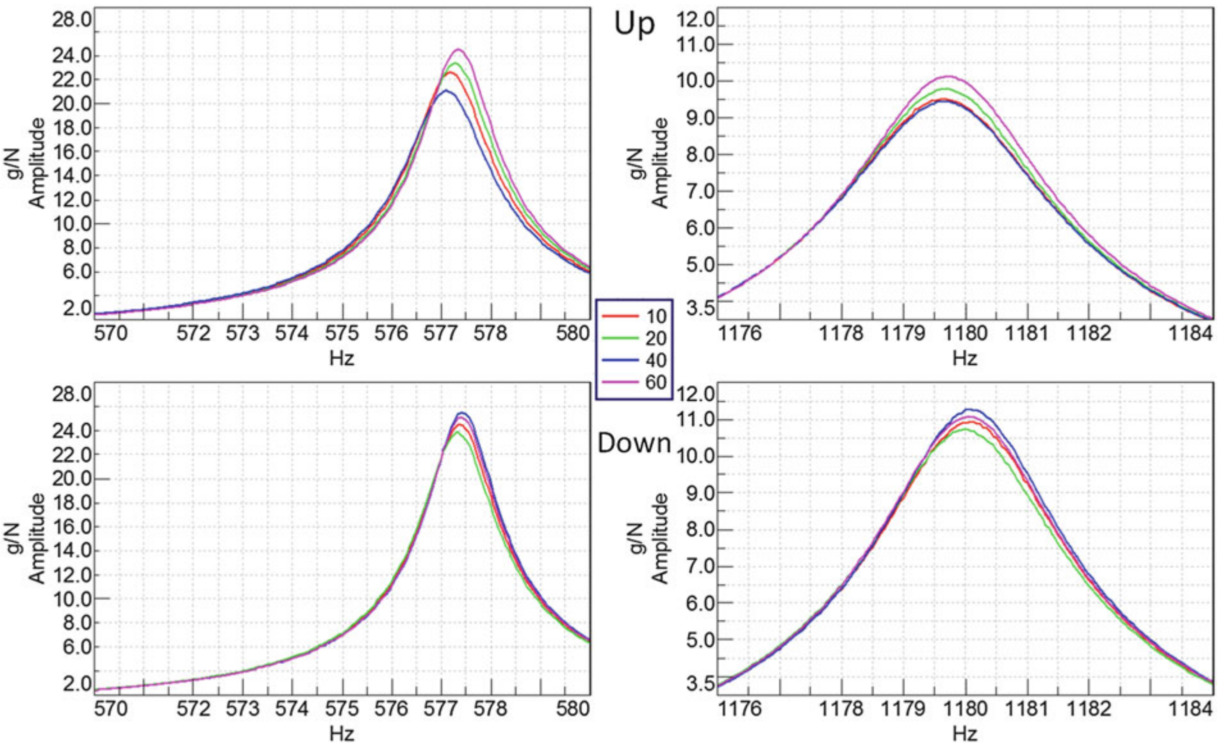


Fig. 48.9 FRFs of 10 g acceleration control to locate optimal number of hold cycles; (*top row*) sweep up, (*bottom row*) sweep down

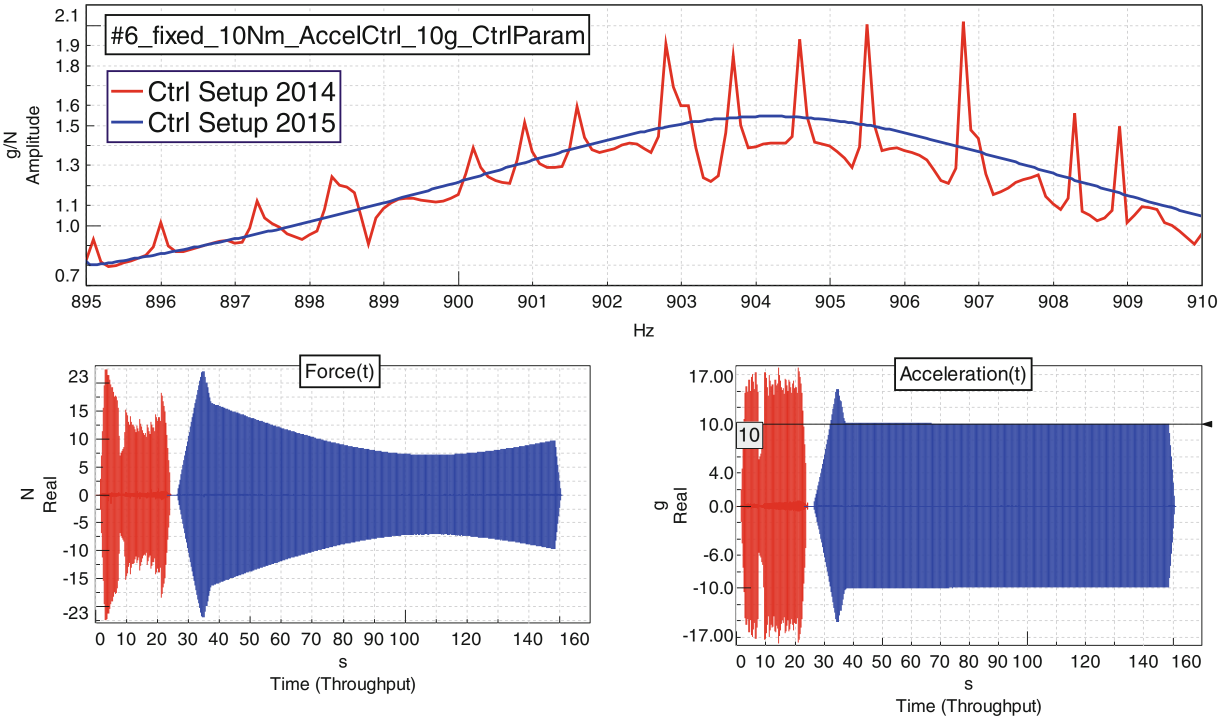


Fig. 48.10 Comparison of the (*top*) FRF and (*bottom*) time signals using (*red*) the parameters from the previous study and (*blue*) optimal parameters

It is not recommended to use force control, unless one has a large shaker that can handle high current. At resonance the force level needed to drive the structure drops drastically. This drop in force requires the amperage going to the shake to increase; the increase may be larger than the shaker can handle. To use force control, low force amplitude would need to be selected; if the force level is set too low a linear analysis maybe tested. Acceleration control gives the best response curve at resonance because the amperage decreases as the amplitude of acceleration at resonance increases, but has the same issue as the force control in off-resonant regions.

48.4 Repeatability Experiments

Once the optimal parameters are identified, the next step is to determine if repeatable results can be achieved. Micro-scale interface differences in roughness cause there to be little repeatability in the response of jointed structures, even from experiment to experiment of the same specimen [4]. To determine repeatability of BR beam results, the system with the "fixed-free" boundary condition is excited using acceleration stepped-sine control. The bolts of the beam are torqued to 5, 10 and 20 Nm. The system is excited around its second bending (174–195 Hz), first torsional (890–930 Hz), and fifth bending (1195–1255 Hz) modes. The ranges are reduced in some of the experiments due to the off-resonance issues with acceleration control; however, all of the experiment ranges fall within those listed. Due to the amplitude variation of each peak's response the acceleration amplitude is controlled at different values, listed in Table 48.2.

To determine the repeatability, the following procedure is used:

1. The beam is torqued to half the desired level, then the desired level
2. A uncontrolled sweep signal near the shakers maximum amperage is run, sweeping up then down
3. The stepped-sine acceleration control is then ran for each peak at all three amplitudes in Table 48.2, starting with the highest amplitude and ending with the lowest
4. After all peaks and amplitudes are ran the beam is disassembled then reassembled using the procedure in step 1
5. Steps 2 through 4 are repeated 3 times for each torque level

An example of the results for the first peak at 10 Nm torque is shown in Fig. 48.11. To better see the shifts in damping and frequency of all the experiments, the values at the peaks are plotted versus the amplitude in Fig. 48.12.

As can be seen in Fig. 48.12 the frequency of first run for each torque level is shifted from the other two runs. This could be that the interface for this first run at each torque level is not settled even with the interfaces being reseated. To produce a smaller range for the frequency locations a fourth run should be performed and the first run should be treated as an additional settling run like the sweeps.

48.5 Conclusions

This research sought to expand the work previous presented in [6] by studying the optimal parameters for controlling the input of a nonlinear system and a process to receive more repeatable results. The optimal parameters and recommendation for this work are:

- The optimal parameters for the LMS Test.Lab Stepped-Sine control are:
  - Low Confidence in Measured System FRF
  - 60 % Error Correction Factor
  - 30 Delay Cycles
  - 40 Hold Cycles

Table 48.2 Control amplitudes for the excitation peaks

Peak	Amplitude 1 (g)	Amplitude 2 (g)	Amplitude 3 (g)
1	0.5	1	2
2	5	10	25
3	1	3	5

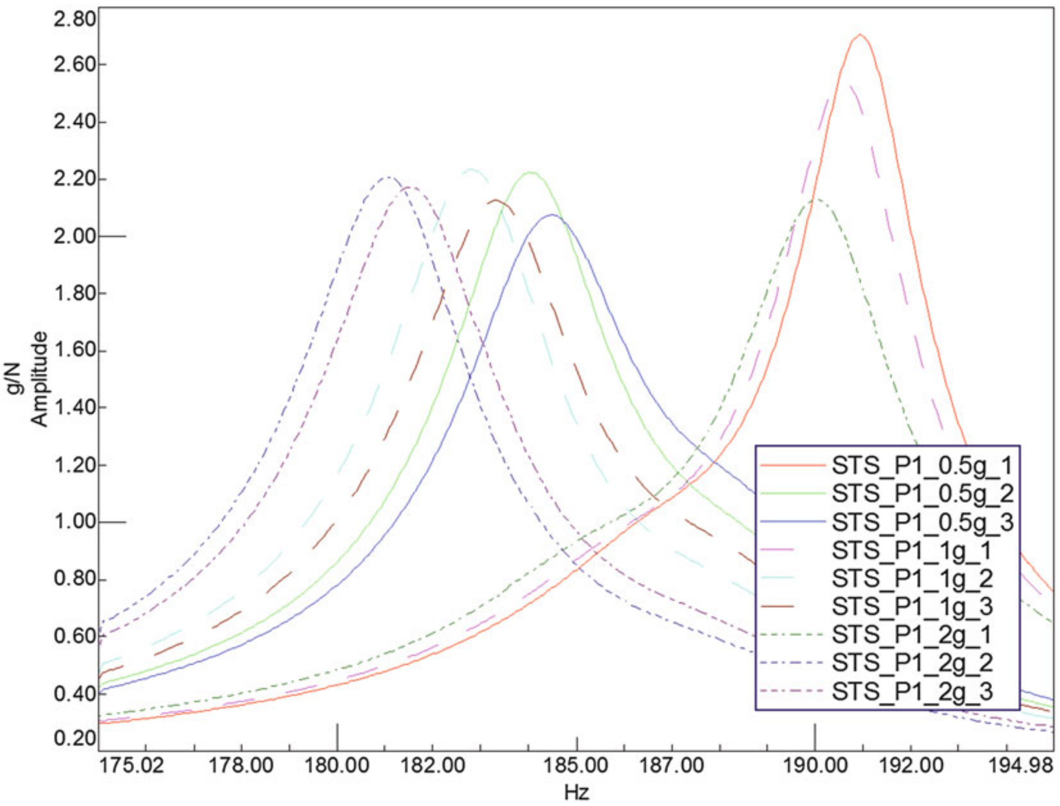


Fig. 48.11 Example repeatability experiment of the first peak at 10 Nm torque

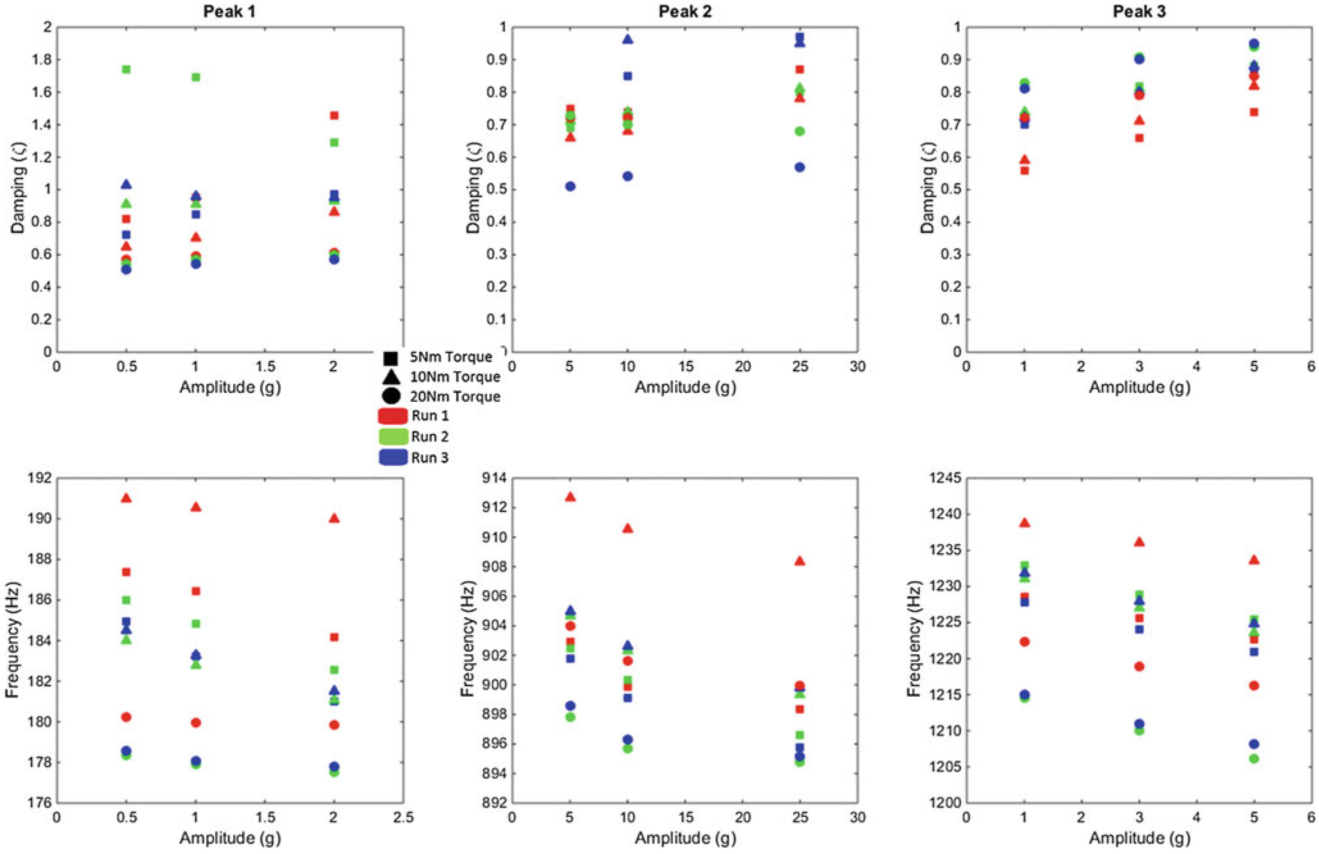


Fig. 48.12 Peak values of damping and frequency versus amplitude of excitation

- Acceleration amplitude control is recommended as the force control has to increase the amperage to the shaker drastically on the resonant peaks
- For fairly repeatable results, the interface should be settled using a sweep signal at the maximum amperage the shaker can handle
- The first stepped-sine signal should be used as a settling signal as well

Future work should aim at the use and development of force control that does not have issues at the resonance of the system, as well as mapping the changes in repeatability of the interface with a large number of tests.

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