Chapter 1
Modal Analysis of a BattleBot Blade

Aakash Umesh Mange and Chad Walber

Abstract In this chapter, the dynamic characteristics of a BattleBot blade is studied. To optimize the design and improve the structural behavior of a test object, modal analysis is a crucial process. Obtaining modal parameters, namely, the natural frequencies, damping, and mode shapes of the unit under test, facilitates in adjusting the dynamic properties and in improving performance. In this case, a heavyweight BattleBot blade that is designed for combat competitions is tested and analyzed. The results are further used to tweak the design of the BattleBot to make it more resistant to damage or breaking of crucial components. Furthermore, these dimensional changes can also help improve the impact force of the BattleBot's blades when it strikes the opponent. Using a new material for the fabrication can also assist in making the robot lighter and stiffer. Hence, a modal test can help make the BattleBot more efficient for the competitions. This work focuses on the experimental setup and discusses the workflow of modal analysis of the BattleBot blade. A modal hammer is used to excite the blade and a uni-axial accelerometer is used to obtain the vibration characteristics. The short pulse induced with a modal hammer excites a wide range of frequencies. To avoid the mass loading effect that is induced with a roving response measurement, the modal test is carried out with a roving excitation method. The test measurements and results are presented in this chapter.

Keywords Modal analysis · BattleBot blade · Modal parameters · Roving hammer test

1.1 Introduction

Executing modal analysis of a structure is crucial in order to analyze the modal parameters of the test object. The natural frequencies, damping, and mode shapes of the unit under test help in adjusting the mechanical properties of the structure by optimizing the design and improving the structural behavior of the test unit.

Icewave is a heavyweight robot designed for robot combat competitions. Icewave is powered by a 15 HP 2-stroke internal combustion engine from a Husqvarna concrete saw that drives a 54 lb. hardened S7 steel blade, rotating at 200 mph at the tips. This internal combustion engine is used to power the horizontal spinner of the robot. Icewave is also rumored to be the loudest robot because of its engine (Fig. 1.1).

Icewave participates in a competition called BattleBots where the robots fight each other in a combat match. The arena has several obstacles that drivers of the robot can use to damage the opposing robot. Icewave creator and team lead believes some of the losses may have been due to the blade not impacting opponents effectively. Because of the power behind Icewave, some of these losses can be attributed to self-inflicted damage from its own rotating horizontal blade. The modal testing will be used to help increase striking effectiveness.

Examination of the horizontal blade through vibration testing to identify the natural (modal) frequencies could provide useful clues as to how performance might be improved. Such vibration testing is typically performed using a shaker or impact hammer. In this instance, vibration testing was performed with an impact hammer. A quick modal survey shows the natural frequencies, damping, and mode shapes of the robot which helps in identifying the weak links in the structure. Hence, modal analysis is a significant part of optimizing the design and performance of these robots.

A. U. Mange (✉)
Crystal Instruments Corporation, Santa Clara, CA, USA
e-mail: amange@go-ci.com

C. Walber
PCB Piezotronics, Depew, NY, USA
e-mail: cwalber@pcb.com

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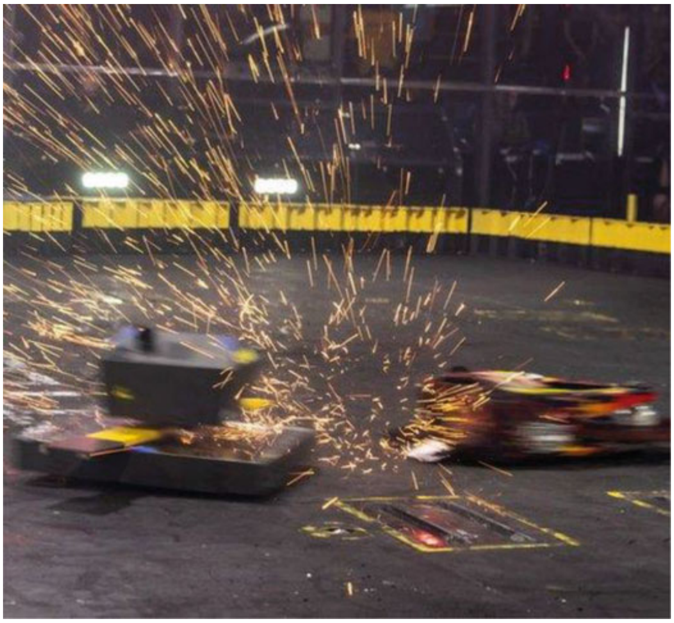


Fig. 1.1 Icewave competing in BattleBot

Fig. 1.2 Icewave bot suspended in modal test frame

1.2 Test Layout

An indoor laboratory was chosen to perform all testing. Temperature was maintained at approximately 70 °F (21 °C). Icewave was suspended via four bungee cord configurations inside an open frame. Connection to Icewave was achieved by attaching each bungee cord configuration to a cord looped through an eye bolt secured to its body. The opposite end of each bungee cord configuration was attached to a cord looped over the top rung of the open frame. Thirty PCB Piezotronics ICP accelerometers (Model 333B30) were stud or epoxy-mounted to Icemaker with coaxial cables (PCB Model 002C10) running back to a Crystal Instruments 32-Channel Data Acquisition System (DAQ), Spider 80X with EDM Modal Software. Excitation of the structure was achieved using a PCB modal hammer (Model 086C03).

A hammer impact test is carried out using a modal hammer and a uni-axial sensor to obtain the vibration characteristics of a robot. The short pulse induced with a modal hammer excites a wide range of frequencies. Another advantage of hammer impact test is quick and easy setup. To avoid the mass loading effect that is induced with a roving response measurement, the modal test is carried out with a roving excitation method (Fig. 1.2).

1.3 Equipment Selection

1.3.1 Accelerometers

In modal analysis applications, the general operating requirements are low acceleration signal levels, low frequencies, high channel counts and long cable runs. This requires sensors designed specifically for modal testing with good resolution, low frequency amplitude and phase, small size, flexible mounting, and TEDS (Transducer Electronic Data Sheet).

The above considerations led to select PCB's Model 333B30 accelerometers for this test, as its specifications were a great match. Its low impedance and constant current operation ensures that signal levels are immune to factors that may introduce environmental noise.

Guidelines for selecting accelerometers for modal testing generally state to choose one with 100 mV/g sensitivity with approximately a milli-g resolution in a moderately small package (typically 5 grams or less). This minimizes the mass loading effect of the sensor. Model 333B30 also has a solid track history in modal testing, including similar structures as rudders, helicopter, and turbine blades.

1.3.2 Hammer

PCB's Model 086C03 Modally Tuned® ICP® instrumented impact hammer features a rugged force sensor that is integrated into the hammer's striking surface. "Modal Tuning" is a feature that ensures the structural characteristics of the hammer do not affect measurement results. This is accomplished by preventing hammer resonances in the frequency range of interest from corrupting the test data, resulting in more accurate and consistent measurements.

The force sensor provides a measurement of the amplitude and frequency content of the energy stimulus that is imparted to a test object. Accelerometers are used in conjunction with the hammer to provide a measurement of the object's structural response due to the hammer blow. A variety of tips supplied with each hammer permit the energy content of the force impulse to be tailored to suit the requirements of the item under test.

1.3.3 Modal Analysis System

Crystal Instruments' efficient Spider 80X system along with its powerful EDM Modal software assists in executing the hammer impact modal test.

The Spider-80X analog input channels provide extremely high precision measurements. Each channel has single-ended or differential AC or DC input coupling. It can also provide IEPE (ICPTM) input mode (AC coupling with a 4 mA constant current from a 22 VDC source) for use with industry-standard accelerometers with built-in amplifiers. The ability to read TEDS (Transducer Electronic Data Sheet) identification from the attached transducer completes the channel's compliance with IEEE 1451.4. Each channel provides an unprecedented dynamic range of 160 dBFS, detecting voltages as small as 600 nV and up to 20 V. This is accomplished by applying two 24-bit analog-to-digital converters to each channel and combining their outputs in accordance with our United States Patent number 7,302,354. The Spider-80X also provides time sync Ethernet connectivity and has 4 GB flash memory for data and program storage.

Using multi-channel data acquisition and analysis software, assists to ascertain a variety of mechanical properties leading to an understanding of an object's structural behavioral characteristics. Items analyzed can include resonance detection, mode shapes, transfer characteristics, and structural health via crack and fatigue detection.

1.3.4 Excitation Method

Of special note with modal accelerometers is the consideration of phase. Channel to channel phase matching throughout the measurement system is paramount for modal testing in the global parameter estimation generated from the measured frequency response data base. With global parameter estimation, the consistency of the frequency response function (FRF) database in terms of natural frequencies is also important. For this reason, it is also advised to instrument all desired measurement points simultaneously, thereby providing consistent mass distribution of the sensors on the test structure. Excitation is achieved by moving the impact hammer about the structure under test. This excitation strategy is known as the Roving Hammer Technique.

The older practice of roving a small set of accelerometers about a structure (Roving Accelerometer Technique) runs the risk of shifting certain component resonances as they are loaded and unloaded with the variable mass distribution of the “roved” set of accelerometers. This results in an inconsistent FRF database, which challenges the parameter estimator, as it expects resonances to be consistent, global properties. An additional benefit of instrumenting all measurement points is the reduction of measurement set time. Essentially, the measurement process takes a “snap shot” of data in time, ensuring that other variances (e.g., visco-elastic properties that can change with temperature) are consistent in the measurement database.

1.4 Experimental Setup and Layout

A mesh configuration of 30 measurement points is distributed through the blades to get good spatial resolution for the mode shapes. Using a flexible band and bungee cord, the robot is hung to imitate a free-free boundary condition (as shown in the experimental setup). The modal hammer with the metal tip is roved through the various measurement points. The responses to the impact excitations is captured using a uni-axial accelerometer that is placed accordingly. Measuring the excitation and response in the vertical direction facilitates in obtaining the out-of-plane mode shapes (Fig. 1.3).

For this modal test, the modes up to 3.5 kHz frequency range are of interest and therefore a sampling rate of 8 kHz is set. A block size of 8192 is selected. A fine frequency resolution of 0.9765 Hz is produced with these configuration settings. Measurements of higher accuracy and reduced noise are obtained by linearly averaging three blocks of data at each measurement DOF.

The broadband spectrum from the metal tip on the modal hammer assists in exciting the modes up to a frequency range of 3.5 kHz. The large block size implemented helps in ensuring natural decay of the structure response without introducing the conventional force-exponential window. Another added advantage of this block size is a finer frequency resolution. With this setup, there will be no leakage and a uniform window can be selected (Fig. 1.4).

The coherence plot helps validate the measurement results; it looks good from the above screenshot. The valleys in the coherence plot occur at the anti-resonances, which indicates that the response level is relatively lower at these corresponding frequencies. So, overall, the inputs and outputs are well correlated in the desirable frequency range.

The DOF of the excitation and response for the measured FRF signals are switched automatically for this roving excitation testing. This can be seen from the Modal Data Selection tab.

The FRF measurement shows good dominant peaks in the 0-3500 Hz frequency band. Overlapping the 30 measured FRFs, several modes can be identified. The good alignment of the peaks indicates the measurement results are good and there was no mass loading effect induced (Fig. 1.5).

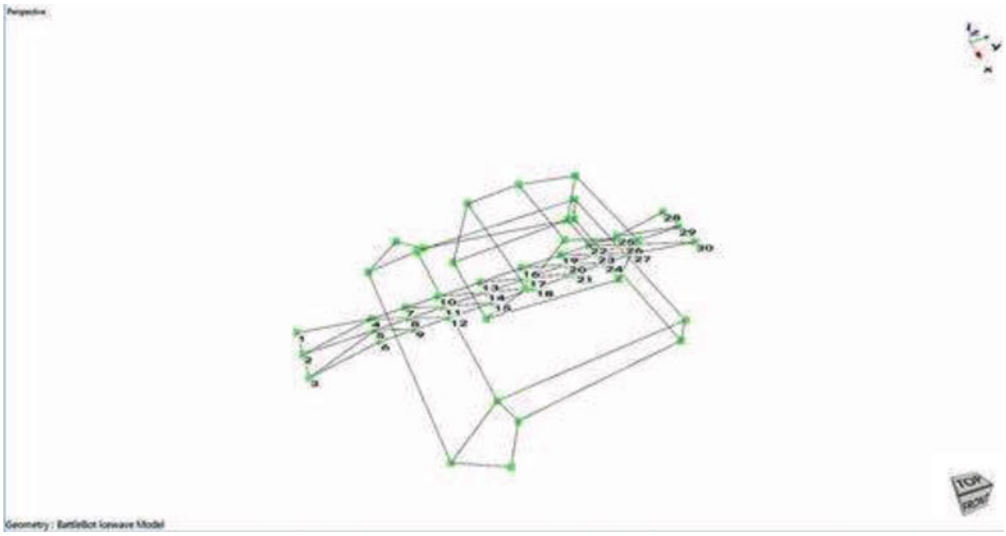
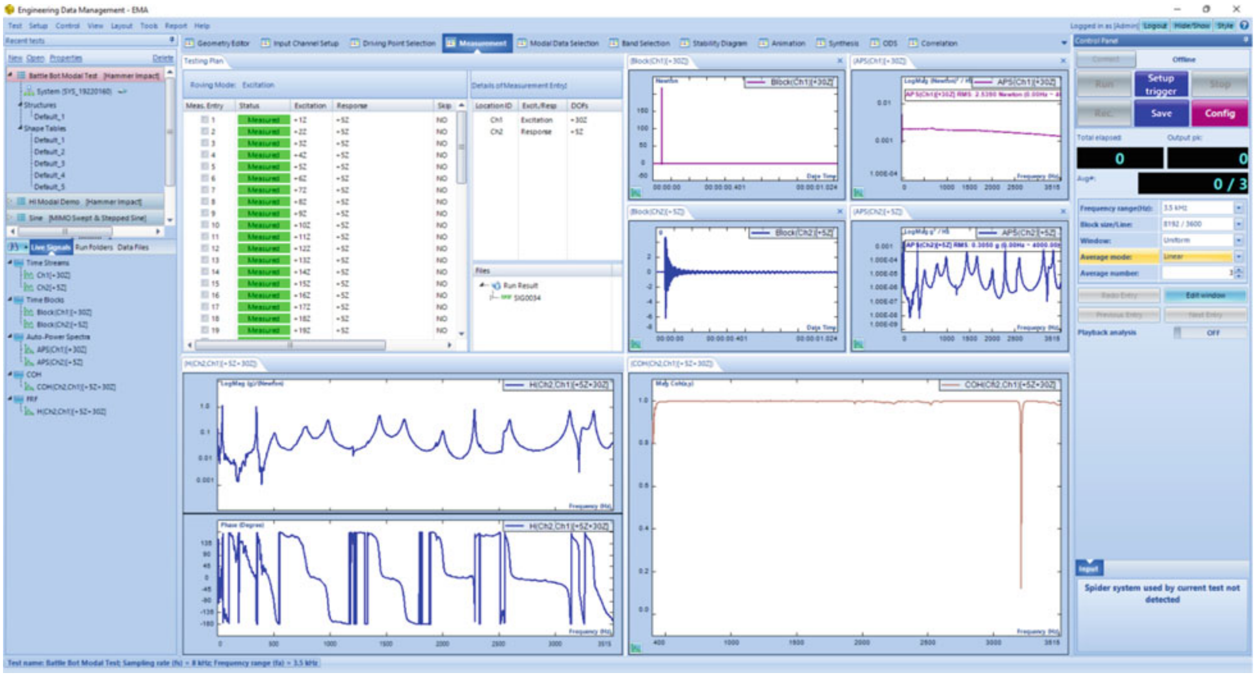


Fig. 1.3 Planned measurement Grid of 333B30 accelerometers



Roving Mode: Excitation

Meas. Entry	Status	Excitation	Response	Skip
☐ 1	Measured	+1Z	+5Z	NO
☐ 2	Measured	+2Z	+5Z	NO
☐ 3	Measured	+3Z	+5Z	NO
☐ 4	Measured	+4Z	+5Z	NO
☐ 5	Measured	+5Z	+5Z	NO
☐ 6	Measured	+6Z	+5Z	NO
☐ 7	Measured	+7Z	+5Z	NO
☐ 8	Measured	+8Z	+5Z	NO
☐ 9	Measured	+9Z	+5Z	NO
☐ 10	Measured	+10Z	+5Z	NO
☐ 11	Measured	+11Z	+5Z	NO
☐ 12	Measured	+12Z	+5Z	NO
☐ 13	Measured	+13Z	+5Z	NO
☐ 14	Measured	+14Z	+5Z	NO
☐ 15	Measured	+15Z	+5Z	NO
☐ 16	Measured	+16Z	+5Z	NO
☐ 17	Measured	+17Z	+5Z	NO
☐ 18	Measured	+18Z	+5Z	NO
☐ 19	Measured	+19Z	+5Z	NO

Details of Measurement Entry

Location ID	Excit./Resp	DOFs
Ch1	Excitation	+30Z
Ch2	Response	+5Z

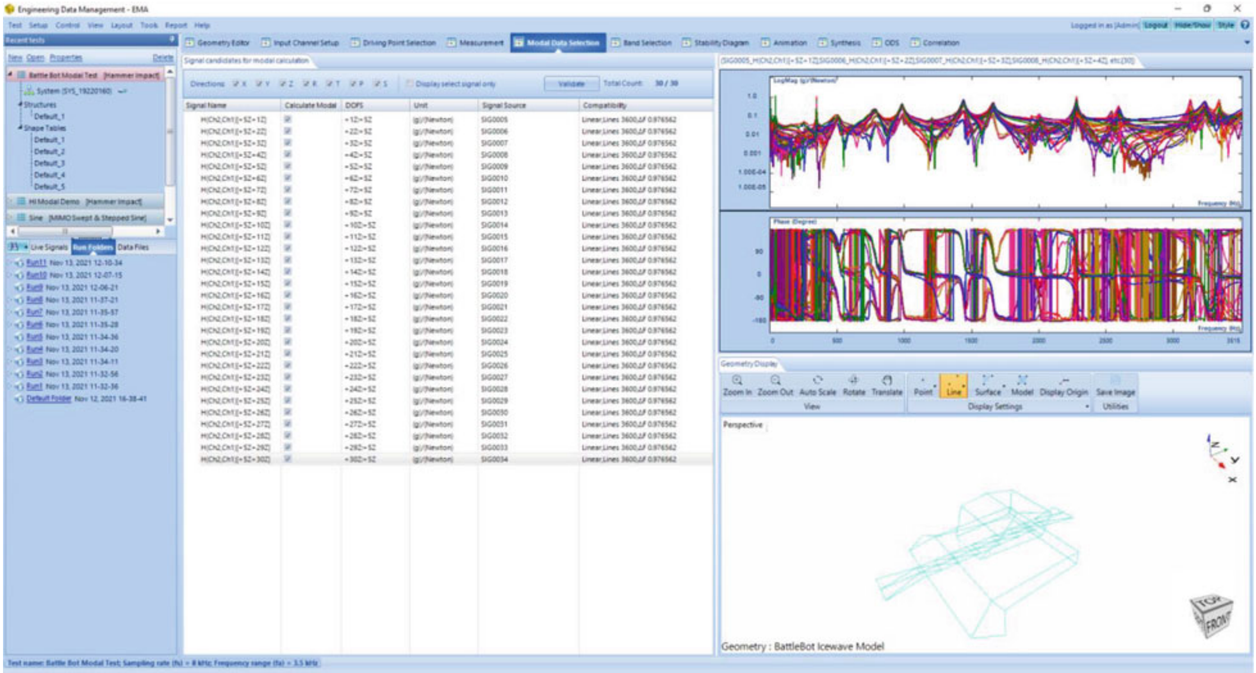
Offline

Total elapsed: 0
Output pk: 0
Avg#: 0 / 3
Frequency range(Hz): 3.5 kHz
Block size/Line: 8192 / 3600
Window: Uniform
Average mode: Linear
Average number: 1
Playback analysis OFF

Spider system used by current test not detected

Test name: Battle Bot Modal Test; Sampling rate (fs) = 8 kHz; Frequency range (fa) = 3.5 kHz

Fig. 1.4 Hammer impact measurement of the robot



Directions: ☑ X ☑ Y ☑ Z ☑ R ☑ T ☑ P ☑ S ☐ Display select signal only

Total Count: 30 / 30

Signal Name	Calculate Modal	DOFS	Unit	Signal Source	Compatibility
H(Ch2,Ch1)[+5Z+1Z]	☑	+1Z/+5Z	(g)/(Newton)	SIG0005	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+2Z]	☑	+2Z/+5Z	(g)/(Newton)	SIG0006	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+3Z]	☑	+3Z/+5Z	(g)/(Newton)	SIG0007	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+4Z]	☑	+4Z/+5Z	(g)/(Newton)	SIG0008	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+5Z]	☑	+5Z/+5Z	(g)/(Newton)	SIG0009	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+6Z]	☑	+6Z/+5Z	(g)/(Newton)	SIG0010	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+7Z]	☑	+7Z/+5Z	(g)/(Newton)	SIG0011	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+8Z]	☑	+8Z/+5Z	(g)/(Newton)	SIG0012	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+9Z]	☑	+9Z/+5Z	(g)/(Newton)	SIG0013	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+10Z]	☑	+10Z/+5Z	(g)/(Newton)	SIG0014	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+11Z]	☑	+11Z/+5Z	(g)/(Newton)	SIG0015	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+12Z]	☑	+12Z/+5Z	(g)/(Newton)	SIG0016	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+13Z]	☑	+13Z/+5Z	(g)/(Newton)	SIG0017	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+14Z]	☑	+14Z/+5Z	(g)/(Newton)	SIG0018	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+15Z]	☑	+15Z/+5Z	(g)/(Newton)	SIG0019	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+16Z]	☑	+16Z/+5Z	(g)/(Newton)	SIG0020	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+17Z]	☑	+17Z/+5Z	(g)/(Newton)	SIG0021	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+18Z]	☑	+18Z/+5Z	(g)/(Newton)	SIG0022	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+19Z]	☑	+19Z/+5Z	(g)/(Newton)	SIG0023	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+20Z]	☑	+20Z/+5Z	(g)/(Newton)	SIG0024	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+21Z]	☑	+21Z/+5Z	(g)/(Newton)	SIG0025	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+22Z]	☑	+22Z/+5Z	(g)/(Newton)	SIG0026	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+23Z]	☑	+23Z/+5Z	(g)/(Newton)	SIG0027	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+24Z]	☑	+24Z/+5Z	(g)/(Newton)	SIG0028	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+25Z]	☑	+25Z/+5Z	(g)/(Newton)	SIG0029	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+26Z]	☑	+26Z/+5Z	(g)/(Newton)	SIG0030	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+27Z]	☑	+27Z/+5Z	(g)/(Newton)	SIG0031	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+28Z]	☑	+28Z/+5Z	(g)/(Newton)	SIG0032	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+29Z]	☑	+29Z/+5Z	(g)/(Newton)	SIG0033	Linear;Lines 3600;ΔF 0.976562
H(Ch2,Ch1)[+5Z+30Z]	☑	+30Z/+5Z	(g)/(Newton)	SIG0034	Linear;Lines 3600;ΔF 0.976562

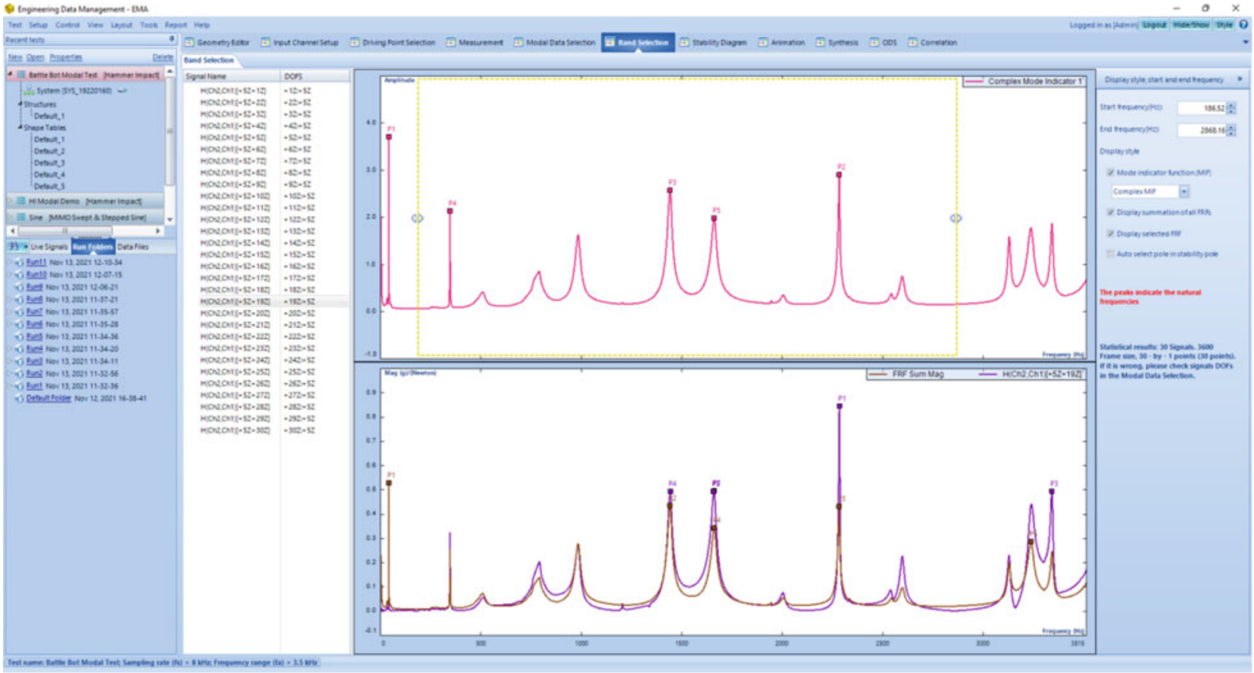
Geometry : BattleBot Icewave Model

Test name: Battle Bot Modal Test; Sampling rate (fs) = 8 kHz; Frequency range (fa) = 3.5 kHz

Fig. 1.5 Modal data selection tab showing the magnitude and phase part of all overlapped FRFs

The Complex Mode Indicator Function (CMIF) is used to locate the modes in the desired frequency range. In addition, the summed FRF is also observed to identify the modes. The frequency domain–based **Poly-X** method is used to curve-fit the FRFs to procure the following stability diagram. Six flexible modes are selected within the desired frequency range (Fig. 1.6).

The stable poles (stable frequency and stable damping) are selected to obtain the natural frequencies and the damping ratios of the interested modes. The residue calculation facilitates in obtaining the mode shapes associated for each of the modes (Figs. 1.7, 1.8, 1.9 and 1.10).



Display style, start and end frequency

Start frequency(Hz): 186.52

End frequency(Hz): 2868.16

Display style

☑ Mode indicator function (MIF)

Complex MIF

☑ Display summation of all FRFs

☑ Display selected FRF

☐ Auto select pole in stability pole

The peaks indicate the natural frequencies

Statistical results: 30 Signals. 3600 Frame size, 30 - by - 1 points (30 points). If it is wrong, please check signals DOFs in the Modal Data Selection.

Test name: Battle Bot Modal Test; Sampling rate (fs) = 8 kHz; Frequency range (fa) = 3.5 kHz

Fig. 1.6 Mode indicator functions to locate and identify the modes in the desired frequency range

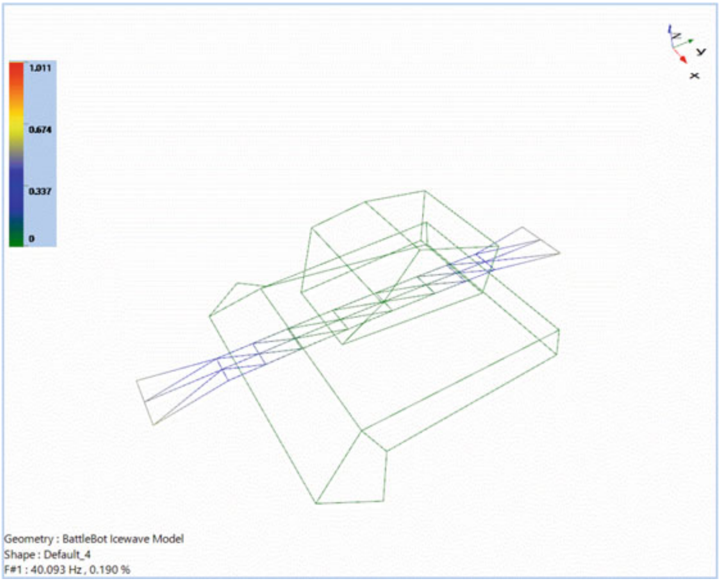


Fig. 1.7 1st order bending mode of the robot at 40 Hz

A quick sweep through the measured FRF dataset can also be carried out to visualize the deformation of the robot at each of the frequencies. With this spectrum data, the modes are uncoupled and hence the operational deflection shapes and the transition through these different frequencies can be analyzed and studied using the ODS function (Fig. 1.11).

1.5 Conclusion

The models suggest combined bending and torsion modes of the striking arm reduces the potential of the destructive force imparted on an opponent.

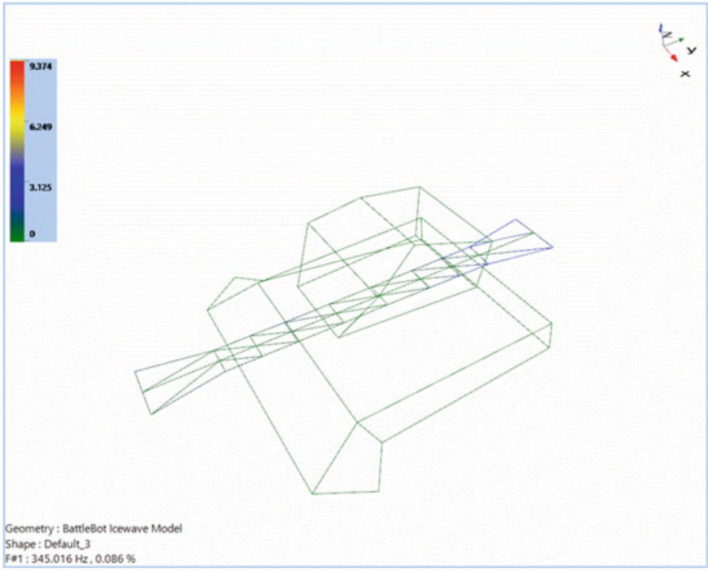


Fig. 1.8 1st order torsion mode of the robot at 345 Hz

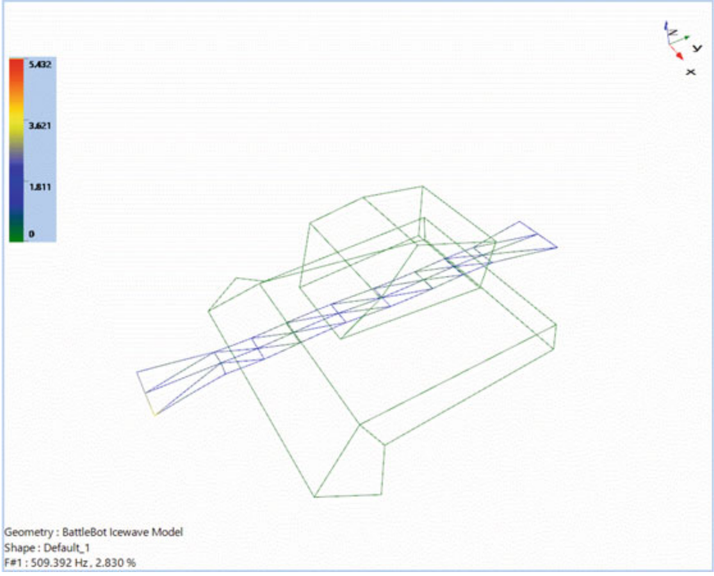
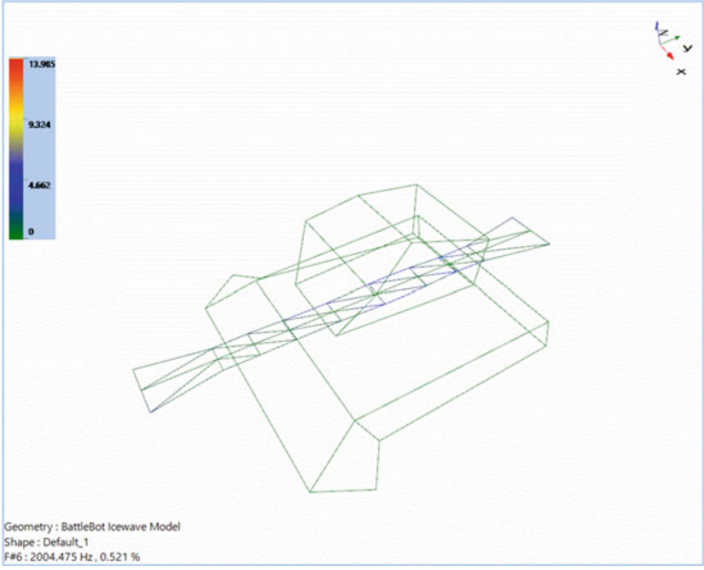


Fig. 1.9 Higher order bending mode of the robot at 509 Hz

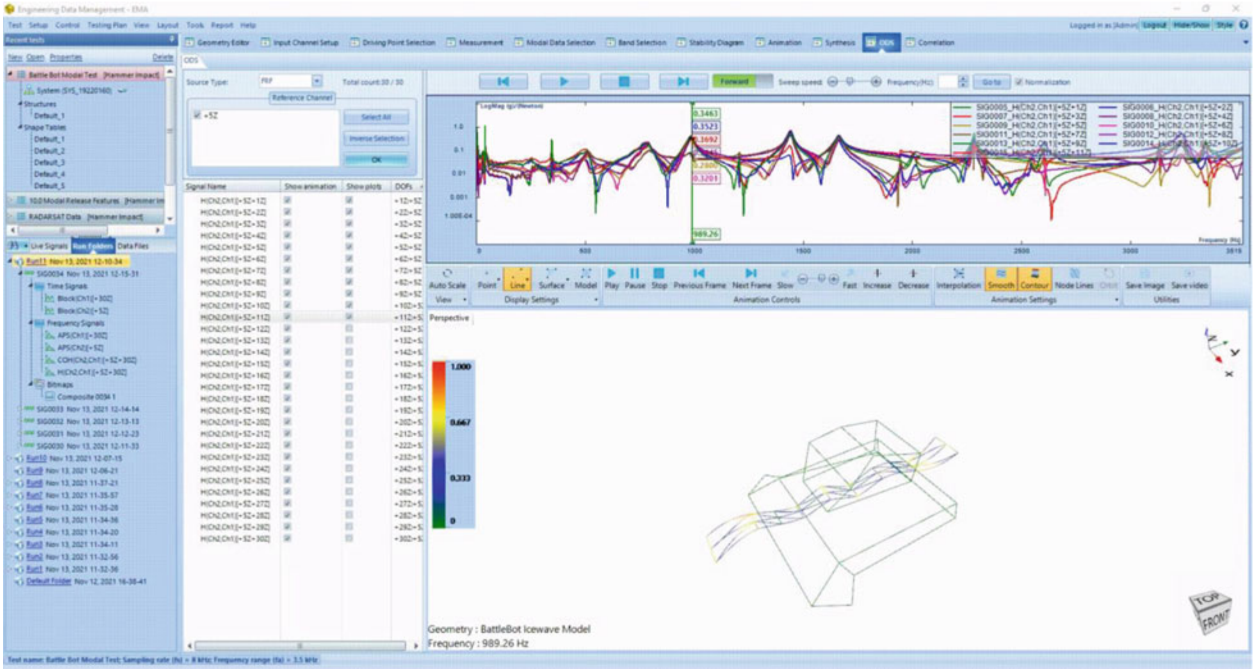
Moving forward, the Icewave team will have multiple options to potentially improve striking performance in combat. One general approach would be to look at ways to “stiffen” the striking arm. This could be achieved by increasing the thickness of the arm and accepting any weight penalties or by evaluating new materials for the arm that are less susceptible to torsion and that will keep a better edge.

A third option would involve modifying the basic design of the arm on the bot. Torsion box physics might be turned to, as a lighter arm constructed with ribs will improve stiffness, yet it begs the question if it will deliver the force needed to incapacitate opponents.



Geometry : BattleBot Icewave Model
Shape : Default_1
F#6 : 2004.475 Hz , 0.521 %

Fig. 1.10 A combination of bending & torsion mode of the robot at 2004 Hz



Geometry : BattleBot Icewave Model
Frequency : 989.26 Hz

Fig. 1.11 Frequency domain ODS of the robot