Investigation of Spinscope module

Expanding the Applications of SpinScope Software

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This project is made in collaboration with

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1 Executive Summary

DAMRC has recently acquired a licensed copy of the 2024 version of SpinScope, part of the MetalMAX family of software developed by Manufacturing Laboratories Inc., following the activities of the P1001-4-7 SpinScope project. Similar to the recent experiences with the TXF tap test software, initial investigations into 2024 SpinScope revealed that the software has additional modules applicable to unique test scenarios that have not yet been utilized to their full potential. These modules are (i) General Data Acquisition, (ii) Frequency Response, (iii) Spindle Condition (iv) Balancing, and (v) Remote Force.

The capabilities and features of the new modules were investigated, and the findings were presented in a midterm evaluation. From this meeting, it was decided that two of the modules, Balancing and Remote Force, should be extensively tested to evaluate the value of these modules in business offerings to Danish industry. The selection of these modules resulted from experience acquired with the other modules during previous projects as well as the accelerated nature of the current investigation.

The Remote Force module, which consists of using the frequency response function between two points to construct an inverse filter capable of reconstructing a force from measurements obtained with an accelerometer, was tested on a KR 10 R900 robot arm at DAMRC. Testing of the module demonstrated that forces could be reconstructed with a relative error on the order of 5%, but that obtaining correct results required advanced knowledge of the MetalMAX software, frequency analysis, and signal processing.

The Balancing module, on the other hand, consists of using the 4-point Single Plane Balancing (SPB) technique to measure the unbalance of rotating machinery and recommend corrective measures. The SPB technique measures acceleration of the spindle with a ‘test mass’ attached in different configurations to determine the current state of unbalance from which recommendations are derived. The module also facilitates measuring the unbalance before and after corrective action is taken to quantify the resulting improvements. Internal testing of the Balancing module was done with the Mazak QuickTurn and DMU 80T machining centers, which demonstrated that the module was intuitive and easy to use but generated inconsistent results between trials.

The activities of the project can be considered a success as the stated objective of gaining experience and competency in the use of the new SpinScope modules was achieved, and the software should be used to assist future projects where applicable. It is also strongly recommended that DAMRC capabilities using the Remote Force module be matured in a future R&D project since the capability of indirectly measuring machining forces without the need for the cumbersome fixtures used with table dynamometers is of particular interest to Danish industry.

2 Introduction

DAMRC has recently acquired a licensed copy of the 2024 version of SpinScope, part of the MetalMAX family of software developed by Manufacturing Laboratories Inc., following the activities of the P1001-4-7 SpinScope project. Deploying SpinScope for the first time in the industry resulted in a success, obtaining insight from the data applicable to predictive maintenance and validating the value proposition of performing such tests in a production environment.

Like the recent experiences with the TXF tap test software, initial investigations into 2024 SpinScope revealed that the software has additional modules applicable to unique test scenarios that have not yet been utilized to their full potential. Gaining competency in these modules may lead to additional benefits for Danish industry in the way of services rendered by DAMRC. Referring specifically to the features available in 2024 version of SpinScope, these modules are:

- General Data Acquisition
- Frequency Response
- Spindle Condition
- Balancing
- Remote Force

This project will investigate these new software possibilities directed to different types of test conditions to gain even better results when collecting and analysing data for tests conducted in internal R&D projects and at client facilities. The idea will be to investigate these modules, develop test plans to evaluate the potential of these modules, and then report on the results of these tests. Modules whose test results show potential may be developed further after the project pending approval from management. The project will be divided into the following stages:

Phase 1: Initial Investigation into the SpinScope software

An initial investigation into the features of the different software modules is conducted, with a view of documenting the workflow, use cases, and applications for each module. Test plans to evaluate the potential business case of each module is created.

Phase 2: Midterm Evaluation

The results of the first phase are presented to management, and a decision is made as to which modules should be tested in phase 3.

Phase 3: Internal Tests of SpinScope Modules

The test plans created in Phase 1 are performed for the software modules selected in Phase 2. The results of the tests are documented, and relevant insights are translated into actional SOPs and communicated to other engineers and staff at DAMRC.

2.1 Pre-analysis

SpinScope is a software designed to facilitate data acquisition in support of general engineering projects and has supplemental features (modules) tailored for specific applications. The user interface of the SpinScope software, presented in Figure 1, has a similar layout to other products in the MetalMAX family of software. To the right of the window displaying the acquired data is a series of buttons arranged to reflect the workflow associated with the software, as is the case in the TXF software. Navigation within SpinScope is achieved using these buttons, the tabs on the right-hand side of the screen, and the drop-down menus at the top of the screen. SpinScope has the additional feature of displaying the selected module in the lower left corner of the screen, and can provide step by step instructions to new users with the “Show Details” button in the lower right corner of the screen, as shown in Figure 1. An example of the instructions provided by the “Show Details” button is presented in Figure 2.

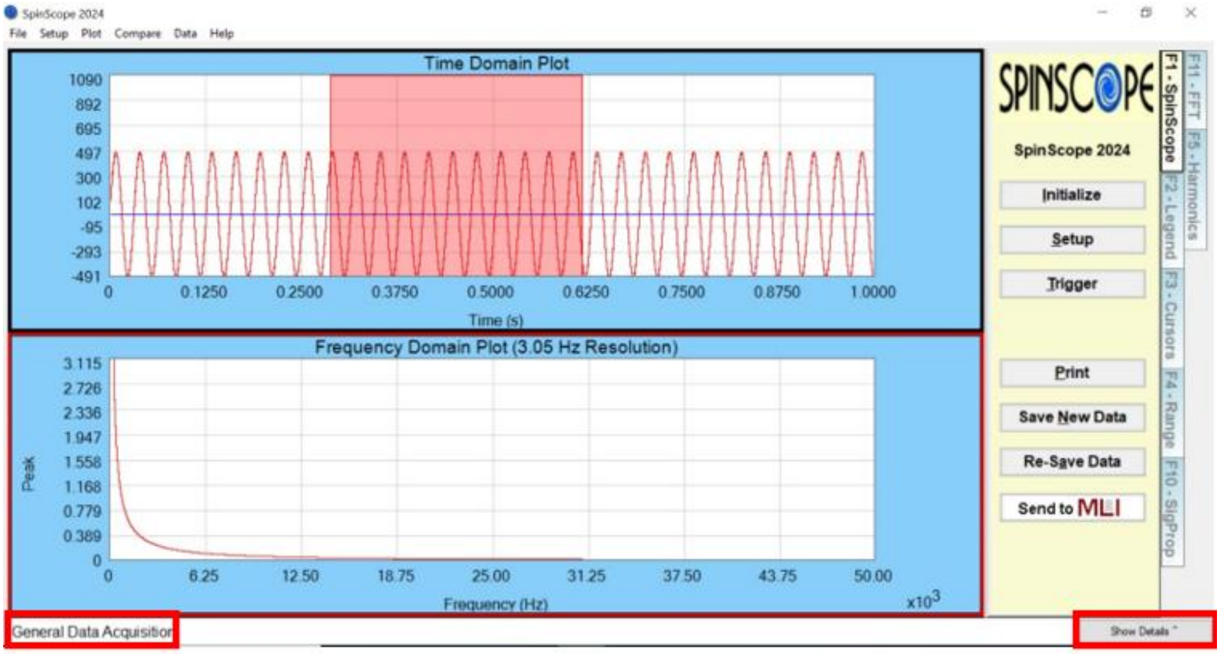
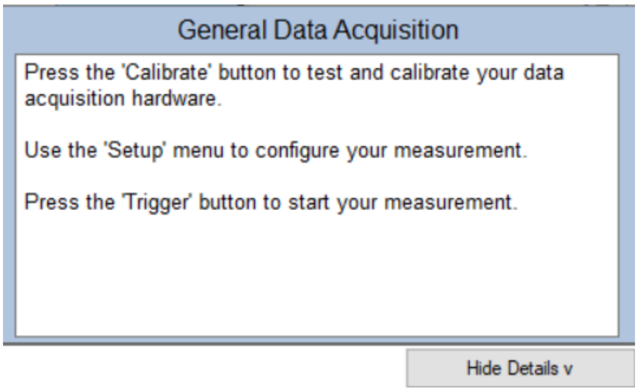


Figure 1 – Main screen of SpinScope 2024.

The currently selected module is displayed in the lower left corner, and the "Show Details" button in the lower right will display detailed step-by-step instructions to the user.



General Data Acquisition

Press the 'Calibrate' button to test and calibrate your data acquisition hardware.

Use the 'Setup' menu to configure your measurement.

Press the 'Trigger' button to start your measurement.

Figure 2 – Example instructions provided by the "Show Details" button.

Since SpinScope data acquisition can be applied to achieve a wide range of objectives, the software is equipped with a versatile set of plotting options to display data in time and frequency domain, including advanced options such as Short Time and Waterfall FFT. SpinScope also has tools to help facilitate data management in the case of piecewise or lengthy measurements. For example, it is possible to merge data obtained from two separate measurements (this option is also available in TXF) or parse the data if only a subset of the measurement signal is of interest. These features are illustrated in Figure 3 and Figure 4.

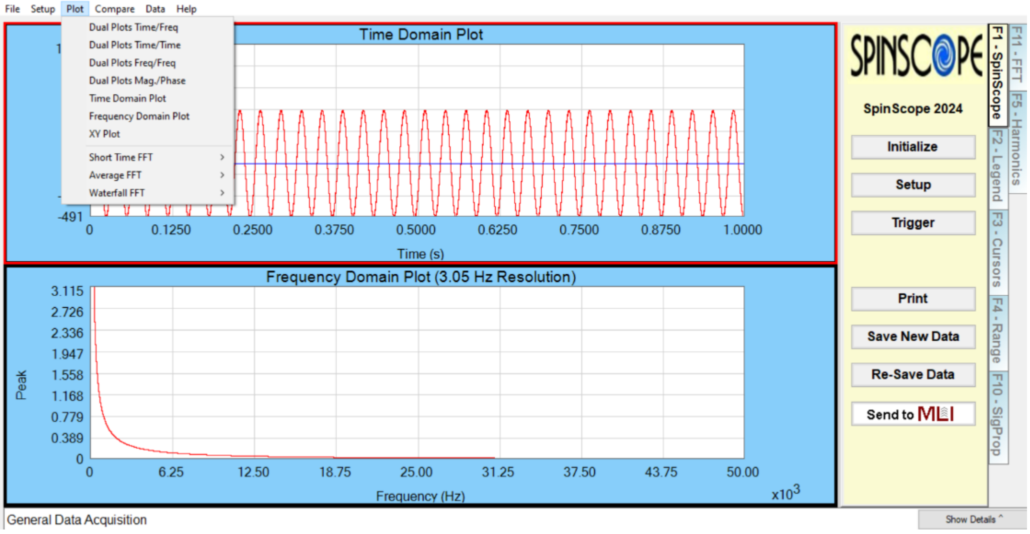


Figure 3 – Time and frequency domain plotting options of data obtained with SpinScope is shown.

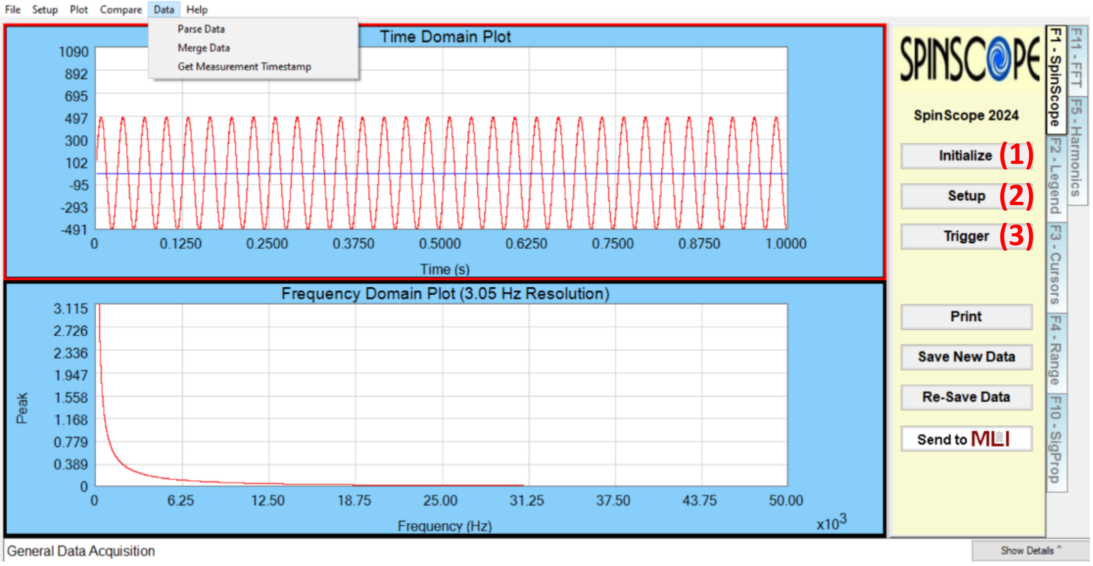
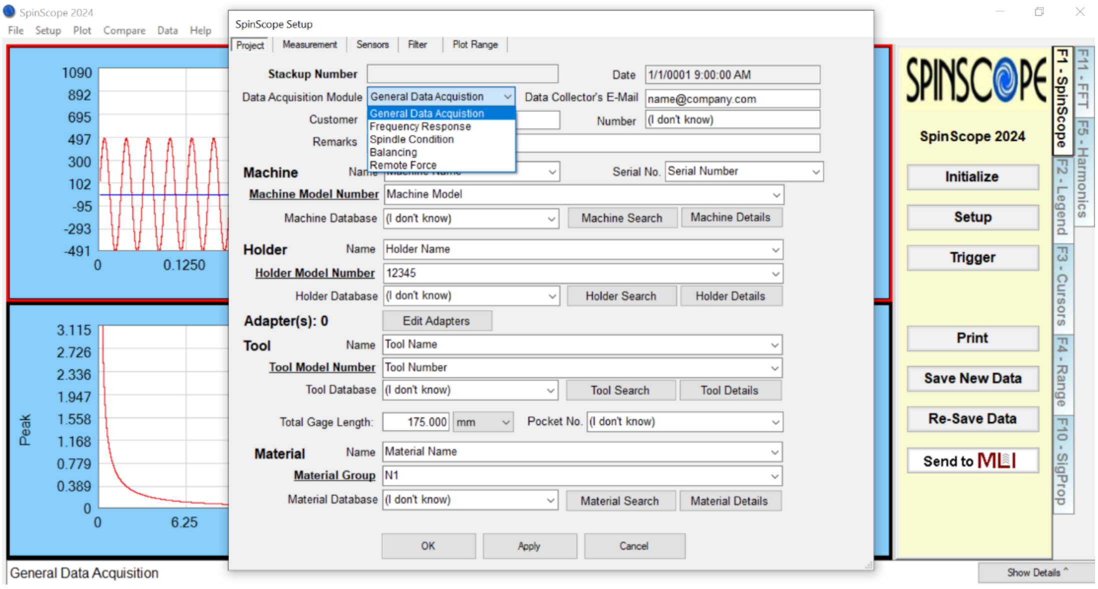


Figure 4 – The location of options to parse and merge data is shown.

Like TXF software, the workflow associated with using SpinScope is to (1) initialize the connected data acquisition device, (2) configure the appropriate settings in the Setup Window, and (3) collect data/perform the test. The process of configuring settings in the Setup Window is similar to what is encountered in TXF, as the option to select the desired SpinScope module is also located in the Project tab of the Setup Window as shown in Figure 5.

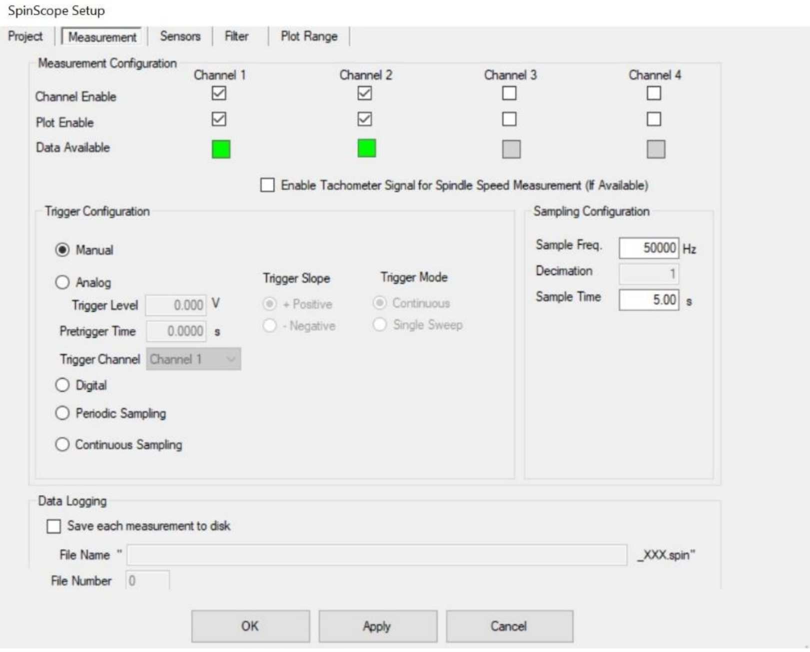


Stackup Number
Date 1/1/0001 9:00:00 AM
Data Acquisition Module General Data Acquistion
Data Collector's E-Mail name@company.com
Customer
Number (I don't know)
Remarks
Machine Name
Serial No. Serial Number
Machine Model Number Machine Model
Machine Database (I don't know)
Holder Name Holder Name
Holder Model Number 12345
Holder Database (I don't know)
Adapter(s): 0
Tool Name Tool Name
Tool Model Number Tool Number
Tool Database (I don't know)
Total Gage Length: 175.000 mm
Pocket No. (I don't know)
Material Name Material Name
Material Group N1
Material Database (I don't know)

Figure 5 – The different software modules can be selected in the Project tab of the Setup window.

However, the setup window for SpinScope also has unique options grouped into tabs in the Setup Window. As SpinScope is intended for data acquisition for a wide array of use cases, the settings in the Measurement Tab provide options governing data acquisition. There are the usual options for specifying data logging and sampling rate, but also under what conditions data acquisition is triggered. For example, it may be desirable to manually trigger data acquisition or to trigger measurement only upon reading an analogue signal having a predetermined Trigger Level, depending on the application. The measurement tab, common to all SpinScope modules, is presented in Figure 6.

Options for filtering the measurement signal are provided in the Filter tab, shown in Figure 7. Various types of filters and window functions (such low pass, high pass, hamming etc.) can be specified from the Filter/Window Type drop down menu. Characteristics of the selected filter/window type can be specified in the (bandwidth, time constant etc.) using the relevant text boxes. Only some options will be editable depending on the selected filter/window type. As shown in the figure, up to ten filters or windows can be specified simultaneously and each filter/window can be applied to one, multiple, or all data channels.



Measurement Configuration

	Channel 1	Channel 2	Channel 3	Channel 4
Channel Enable	☑	☑	☐	☐
Plot Enable	☑	☑	☐	☐
Data Available	🟩	🟩	▢	▢

☐ Enable Tachometer Signal for Spindle Speed Measurement (If Available)

Trigger Configuration

● Manual
○ Analog
Trigger Level 0.000 V
Pretrigger Time 0.0000 s
Trigger Channel Channel 1
Trigger Slope: ● + Positive ○ - Negative
Trigger Mode: ● Continuous ○ Single Sweep
○ Digital
○ Periodic Sampling
○ Continuous Sampling

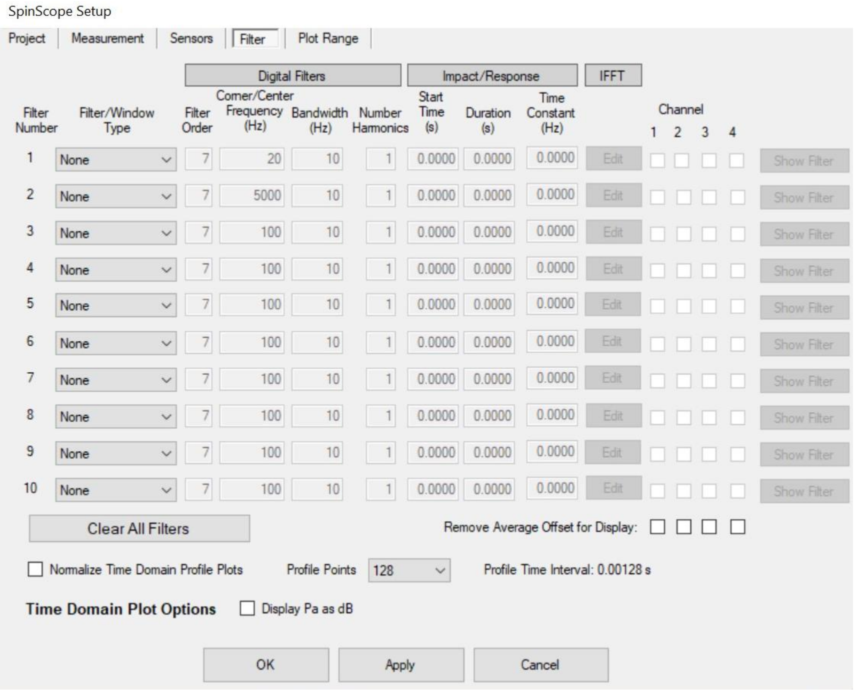
Sampling Configuration

Sample Freq. 50000 Hz
Decimation 1
Sample Time 5.00 s

Data Logging

☐ Save each measurement to disk
File Name " _XXX.spin"
File Number 0

Figure 6 – The Measurement tab (common to all modules) of the Setup window is shown.



Filter Number	Filter/Window Type	Filter Order	Corner/Center Frequency (Hz)	Bandwidth (Hz)	Number Harmonics	Start Time (s)	Duration (s)	Time Constant (Hz)		Channel 1	Channel 2	Channel 3	Channel 4	
1	None	7	20	10	1	0.0000	0.0000	0.0000	Edit	☐	☐	☐	☐	Show Filter
2	None	7	5000	10	1	0.0000	0.0000	0.0000	Edit	☐	☐	☐	☐	Show Filter
3	None	7	100	10	1	0.0000	0.0000	0.0000	Edit	☐	☐	☐	☐	Show Filter
4	None	7	100	10	1	0.0000	0.0000	0.0000	Edit	☐	☐	☐	☐	Show Filter
5	None	7	100	10	1	0.0000	0.0000	0.0000	Edit	☐	☐	☐	☐	Show Filter
6	None	7	100	10	1	0.0000	0.0000	0.0000	Edit	☐	☐	☐	☐	Show Filter
7	None	7	100	10	1	0.0000	0.0000	0.0000	Edit	☐	☐	☐	☐	Show Filter
8	None	7	100	10	1	0.0000	0.0000	0.0000	Edit	☐	☐	☐	☐	Show Filter
9	None	7	100	10	1	0.0000	0.0000	0.0000	Edit	☐	☐	☐	☐	Show Filter
10	None	7	100	10	1	0.0000	0.0000	0.0000	Edit	☐	☐	☐	☐	Show Filter

Remove Average Offset for Display: ☐ ☐ ☐ ☐

☐ Normalize Time Domain Profile Plots

Profile Points: 128

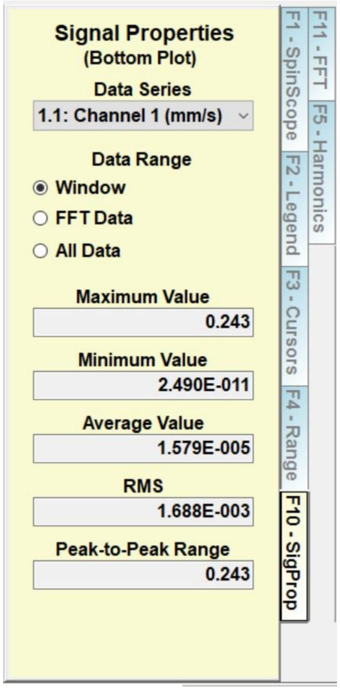
Profile Time Interval: 0.00128 s

Time Domain Plot Options ☐ Display Pa as dB

Figure 7 – The Filter tab (common to all modules) of the Setup window is shown.

All the modules in SpinScope have additional options accessible through the tabs on the right-hand side of the screen for manipulating the measurement data as needed. Besides the usual options for specifying plot range and displaying data cursors and legends, options exist for displaying key signal properties and configuring the properties of the FFT window and optional harmonic filter. The side panels containing these settings are shown in Figure 8 - Figure 9.

The Signal Properties side panel (presented in Figure 8) provides the means for rapidly obtaining commonly used statistical metrics of the measurement signal, such as max, min, and RMS value. As shown in the figure, these metrics can be displayed for the time or frequency domain data or both and can be used for any measurement channel.


Signal Properties
(Bottom Plot)

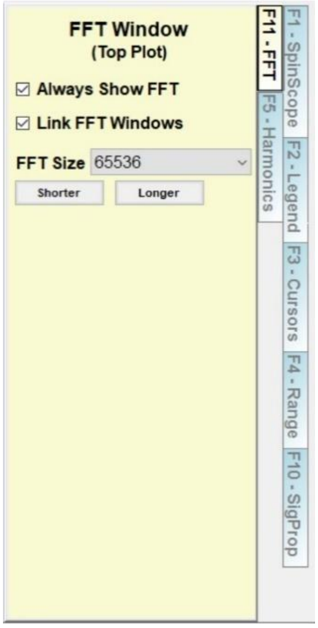
Data Series: 1.1: Channel 1 (mm/s)

Data Range
● Window
○ FFT Data
○ All Data

Maximum Value: 0.243
Minimum Value: 2.490E-011
Average Value: 1.579E-005
RMS: 1.688E-003
Peak-to-Peak Range: 0.243

Figure 8 – Signal Properties side panel.

SpinScope provides the means for displaying the measurement signal in both the time and frequency domain. This is done by obtaining measurement signals in the time domain and then applying fast Fourier transform (FFT) to the data to obtain the corresponding frequency information. An FFT window is applied to apply FFT to a specific segment of the time domain data, like the working principle of the Analysis Window in Harmonizer software. Options for configuring this window is provided in the FFT window, shown in Figure 9.

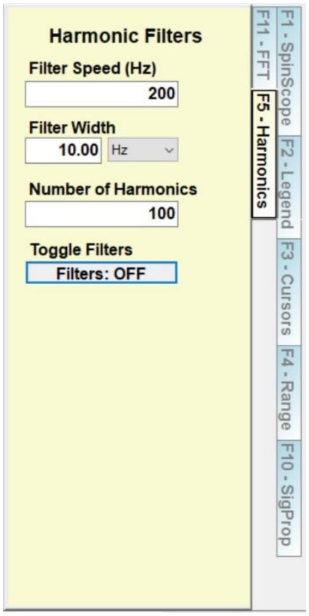

FFT Window
(Top Plot)

☑ Always Show FFT
☑ Link FFT Windows

FFT Size: 65536

Figure 9 – FFT Window side panel.

SpinScope provides the means for filtering out specific frequencies and their harmonics. This can be applied to remove, for example, frequencies corresponding to spindle rotation speed or ambient frequencies from the measurement signal. The harmonic filter work principle is similar to the one used in Harmonizer. The Harmonic Filters window (shown in Figure 10) allows the user to specify the filter center frequency ("Filter Speed"), the filter width, and the number of harmonics of the center frequency that should be filtered out.


Harmonic Filters

Filter Speed (Hz) 200

Filter Width 10.00 Hz

Number of Harmonics 100

Toggle Filters: Filters: OFF

Figure 10 – Harmonic Filter side panel.

The workflow and options discussed above are common to all SpinScope modules. Features and characteristics specific to each module are presented in the following subsections, along with potential use cases.

2.2 Module 1: General Data Acquisition

The General Data Acquisition Module consists of the "default" settings and workflow described above but can be applied to many use cases. For example, in the incubator project P1001-4-7, the General Data Acquisition Module (2009 (32-bit) version of SpinScope) was used to collect raw acceleration data from test bearings, which were subsequently analysed offline.

2.3 Module 2: Frequency Response

The Frequency Response Module is used to obtain the Frequency Response Function of a dynamic system or structure in a manner like impact hammer tap tests used in TXF software. Using Frequency Response Module, it is possible to attach an instrumented impact hammer and accelerometer to the DAQ device, perform tap tests using SpinScope, and obtain the FRF of the tested structure as in the TXF software. The Frequency Response Module in SpinScope does not generate stability lobe diagrams like TXF, but the user has more flexibility and freedom in selecting the configuration of the hammer impact and accelerometer location whereas the measurement configurations in TXF are limited to predefined options (for example tool point FRF in x and y direction, workpiece FRF in x and y direction, etc.). As a result, the user can apply Frequency Response Module to identify the structural dynamics of various systems, thereby expanding the applications and potential of tap testing.

The main user interface of SpinScope, Frequency Response Module, is presented in Figure 11, which features an additional button in the side panel for accepting or rejecting measurements obtained from an individual impact. The Frequency Response Module also provides additional plotting options for displaying the obtained FRF after all measurements are obtained, along with the corresponding coherence (see figure Figure 12). Unlike TXF, the time domain measurement signal of both hammer excitation and response measurement are displayed in the same window, while the frequency domain data corresponding to each measurement channel are likewise presented in the same window.

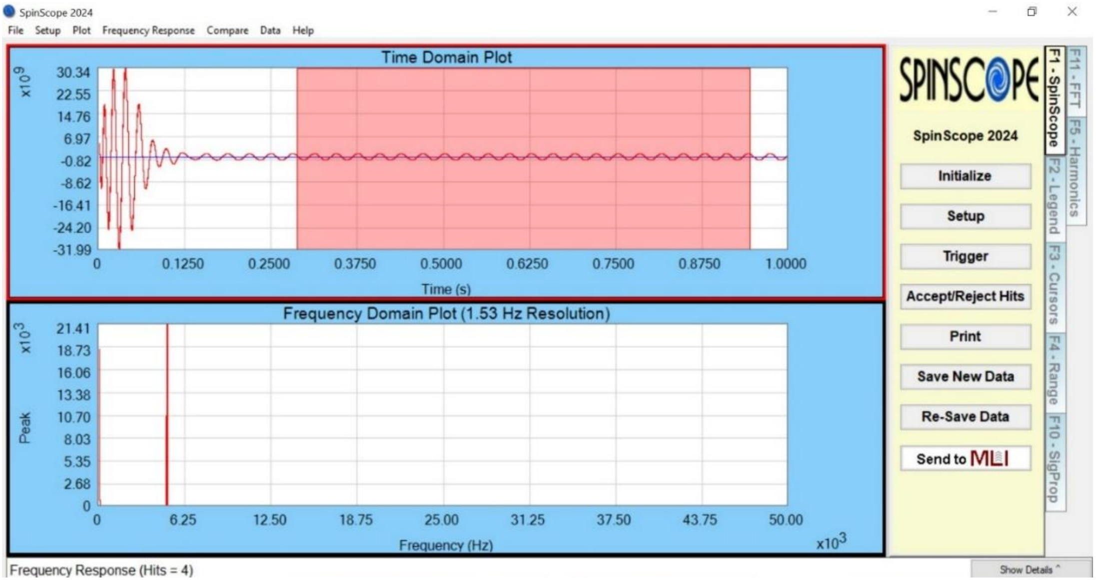


Figure 11 – Main SpinScope screen when using the Frequency Response Module, featuring an additional button in the side panel for accepting/rejecting hits.

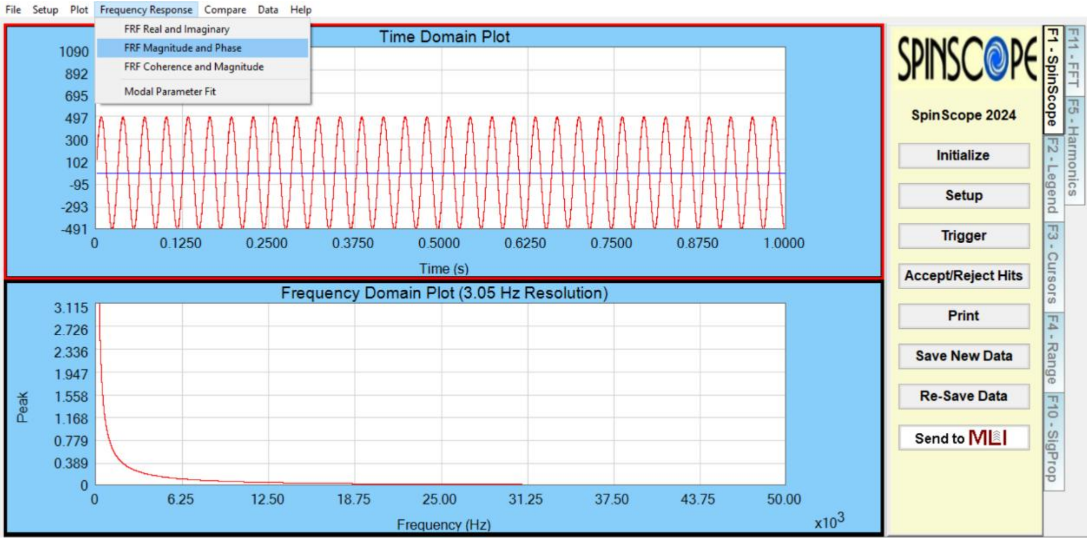
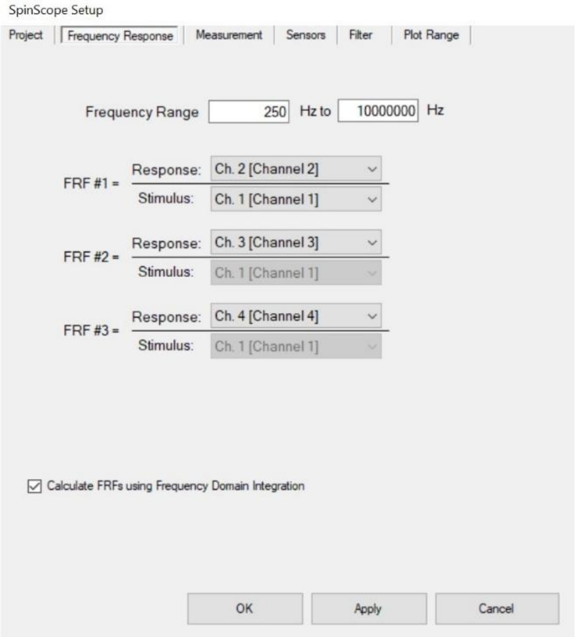


Figure 12 – The Frequency Response Module features additional plotting options for displaying the obtained FRF and measuring its coherence.

An advantage of using the Frequency Response Module in SpinScope is that all four channels of the DAQ device can be leveraged to obtain multiple FRFs simultaneously. This is illustrated in the Frequency Response tab in the Setup Window (presented in Figure 13), which allows the user to specify the stimulus and response channels for up to 3 simultaneous FRF measurements as well as the frequency range for these measurements. Specifying the stimulus channel for FRF #1 in the figure necessarily determines the stimulus channel for the other FRF measurements. The response signal for any FRF can also be set to 'None.'



Frequency Range 250 Hz to 10000000 Hz

FRF #1 = Response: Ch. 2 [Channel 2]
Stimulus: Ch. 1 [Channel 1]

FRF #2 = Response: Ch. 3 [Channel 3]
Stimulus: Ch. 1 [Channel 1]

FRF #3 = Response: Ch. 4 [Channel 4]
Stimulus: Ch. 1 [Channel 1]

☑ Calculate FRFs using Frequency Domain Integration

Figure 13 – The Frequency Response tab allows the user to configure the simultaneous measurement of multiple FRFs.

Minor changes to the settings in the Setup Window exist as a result of selecting the Frequency Response module. In the measurement tab, it is only possible to trigger a measurement using the ‘Analog’ option, since (as is the case with tap testing using TXF) it is expected that measurement is triggered by a predetermined trigger voltage from the stimulus channel, corresponding to the initial hammer impact. Predefined filters in the filters tab are also provided by default to facilitate FRF measurement. The properties of these filters can be altered for advanced cases if necessary. It is expected that FRFs obtained in SpinScope can be imported into TXF. This functionality has not yet been tested.

Special attention must be taken concerning the settings in the Sensors tab in SpinScope if SpinScope FRFs are to be imported into TXF. There are distinct differences between FRFs where the response signal is an acceleration, velocity, or displacement (which are described in (Ewins, 2009)), but TXF uses receptance FRF (displacement response) to generate SLDs. Therefore, it is necessary to carefully specify the appropriate integration/differentiation setting in the Sensors tab if additional analysis using TXF is intended.

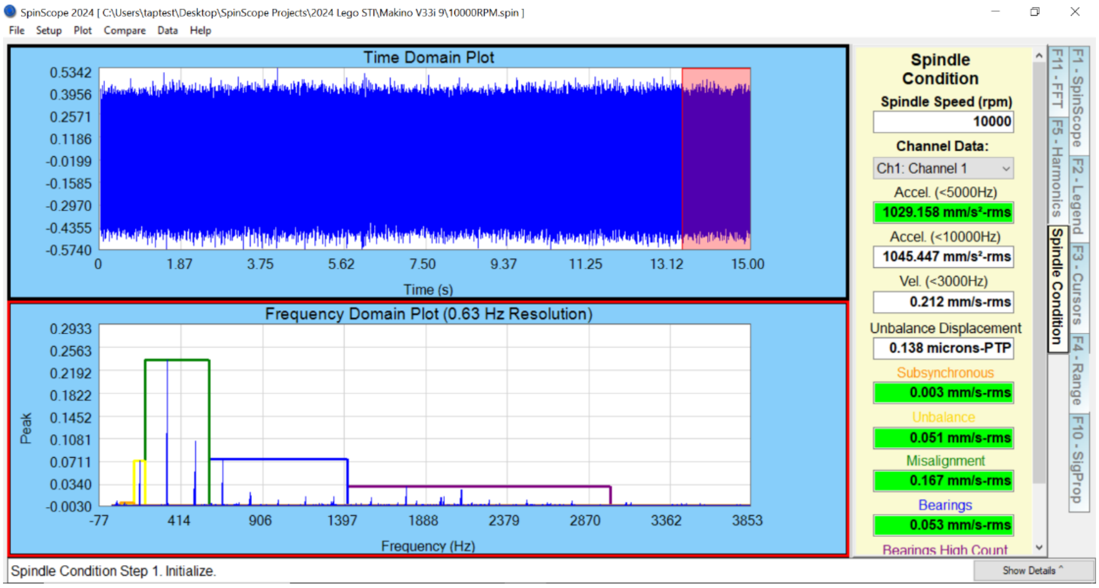
There are many potential use cases for the Frequency Response Module. The Frequency Response Module has already been used to perform tap tests of a drilling tool in the “Advanced modal analysis for machining holes incubator project”. In this case, the Frequency Response module in SpinScope was used to measure two FRFs simultaneously in a semi-novel measurement configuration to capture torsional vibration modes. It is expected that the module will be effective in future internal research projects where FRFs of test specimens or structures need to be measured.

Future applications are also numerous. The flexibility provided by the Frequency Response Module makes the technology suitable for identifying the FRFs of general structures in addition to the tool point FRFs that DAMRC has experience with. For example, FRF measurement and modal analysis has long been used in the Civil Engineering field (al. A. C., 2006), and similar techniques could theoretically be applied to the more detailed analysis of custom fixtures or otherwise novel machining setups.

FRF measurement and modal analysis have been performed using a number of techniques besides tap testing (al. A. C., 2006), and the same potential exists with the Frequency Response Module since SpinScope is technically sensor agnostic, meaning that the user only needs to specify the stimulus channel, sensitivity, etc. and is not compelled to use a particular hammer (or sensor). Therefore, it is hypothetically possible to use Frequency Response Module with an excitation source other than the conventional impact hammer, for example by using shakers which were investigated in (Peres, 2012). Finally, the flexibility in measurement configuration and system identification can be applied in advanced research, for example in the areas of cutting force reconstruction or state estimation (al. E. L., 2012).

2.4 Module 3: Spindle Condition

The Spindle Condition Module is intended for assessing the health of rotating machinery, for example, machine tool spindles, and has applications in predictive maintenance. A major characteristic of the module is the division of the frequency data into different frequency bands corresponding to different spindle fault conditions. A description of the physical meaning of these different bands and statistical measures for the overall signal and for each individual frequency band are provided in a unique “Spindle Condition” side panel as shown in Figure 14 and is also available in the “Legend” tab. The Spindle Condition Module is therefore capable of providing powerful diagnostic tools for the user.



Spindle Condition

Spindle Speed (rpm): 10000

Channel Data: Ch1: Channel 1

Accel. (<5000Hz): 1029.158 mm/s²-rms

Accel. (<10000Hz): 1045.447 mm/s²-rms

Vel. (<3000Hz): 0.212 mm/s-rms

Unbalance Displacement: 0.138 microns-PTP

Subsynchronous: 0.003 mm/s-rms

Unbalance: 0.051 mm/s-rms

Misalignment: 0.167 mm/s-rms

Bearings: 0.053 mm/s-rms

Bearings High Count

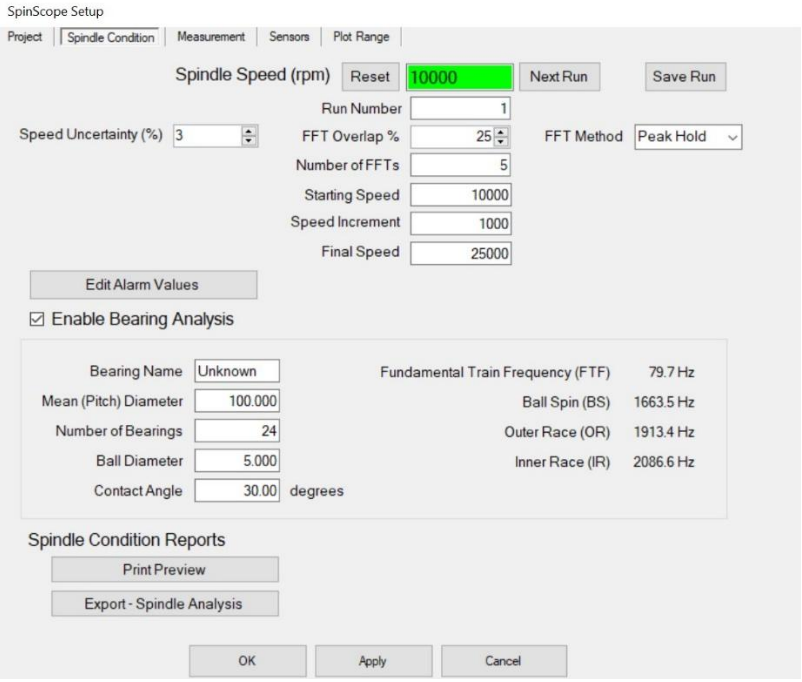
Spindle Condition Step 1. Initialize.

Figure 14 – The Spindle Condition Module of SpinScope. The frequency domain in the bottom window is divided into different frequency bands corresponding to different faults as specified in the side panel.

Selecting the Spindle Condition Module adds the Spindle Condition tab and removes the Filter tab from the Setup Window. The Spindle Condition tab, shown in Figure 15, has settings for specifying the operating speed (spindle speed) of the machine, configuring test parameters, and providing data for the rolling element bearings in the spindle.

Information provided in this tab must be accurate. The specified spindle speed and the data entered under “Enable Bearing Analysis” are used in the evaluation of the frequency bands shown in Figure 14. Frequency bands for faults such as Unbalance, Misalignment etc. are calculated as multiples of the specified spindle speed, while data provided for bearing analysis must be accurate to generate correct bearing fault frequencies.

The settings in the Spindle Condition tab also govern tests performed with SpinScope. It has been observed that rotating machinery can exhibit speed-dependent dynamics (B. Fang, 2019) (S. Lu, 2016). Therefore, typical Spindle Condition tests with SpinScope consist of recording measurement data at a given spindle speed and then iterating the procedure while “sweeping” through a range of spindle speeds. With this in mind, the settings in Spindle Condition tab facilitate workflows involving tests at multiple spindle speeds. By specifying the number of runs, starting speed, ending speed, and speed increment, the user can rapidly obtain spindle data at multiple spindle speeds when these settings, are used in conjunction with the “Next Run” and “Save Run” buttons. Finally, the “Edit Alarm Values” button can be used to change the setpoint at which various alarms are raised and create custom alarms.



Spindle Speed (rpm) 10000
Run Number 1
Speed Uncertainty (%) 3
FFT Overlap % 25
FFT Method Peak Hold
Number of FFTs 5
Starting Speed 10000
Speed Increment 1000
Final Speed 25000

☑ Enable Bearing Analysis

Bearing Name Unknown
Mean (Pitch) Diameter 100.000
Number of Bearings 24
Ball Diameter 5.000
Contact Angle 30.00 degrees

Fundamental Train Frequency (FTF) 79.7 Hz
Ball Spin (BS) 1663.5 Hz
Outer Race (OR) 1913.4 Hz
Inner Race (IR) 2086.6 Hz

Figure 15 – Spindle Condition tab in the Setup Window of SpinScope.

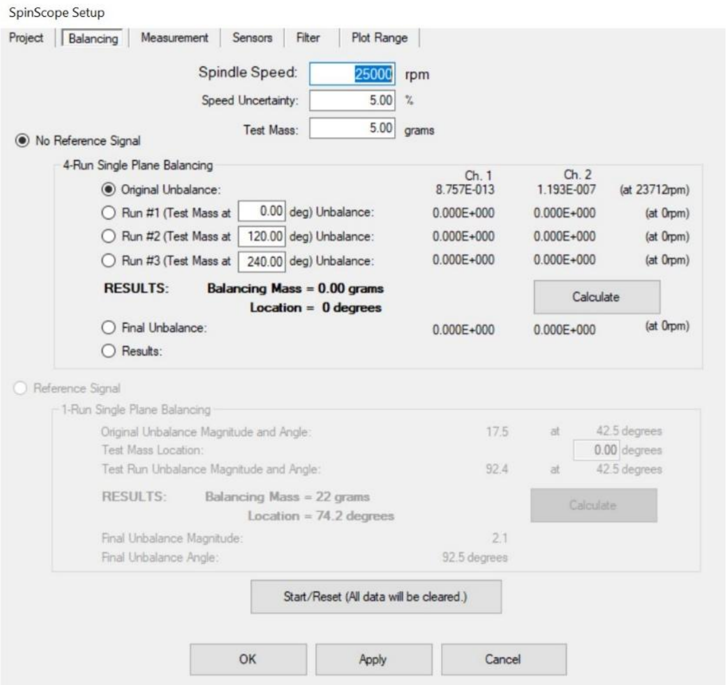
Following the activities of the P1001-4-7 SpinScope incubator project, DAMRC acquired a licensed of SpinScope 2024 and tested its capabilities in the industry to gain and transfer insights about best practices for predictive maintenance. The Spindle Condition module was used in an initial test instead of the frequency analysis techniques developed during the incubator project due to a lack of bearing data in the tested machine tool spindles. The experience demonstrated that valuable insight can be obtained from Spindle Condition module even when working with incomplete data from clients.

2.5 Module 4: Balancing

Enabling the Balancing module of SpinScope, which provides the means of quantifying unbalance in general rotating machinery in addition to CNC spindles, adds the Balancing tab (Figure 16) to the Setup window while leaving other aspects of the user interface on the main screen the same as the default.

As shown in the figure, the workflow associated with this module involves triggering multiple measurements as part of a 4-Run Single Plane Balancing (SPB) test procedure. The SPB test procedure consists of recording acceleration signals during normal operation and then measuring additional acceleration signals after attaching a test mass that is offset from center, inducing an unbalanced state. Unbalance is measured when the test mass is positioned at three distinct angular positions. The data from the four measurements are combined to calculate the inherent unbalance of the rotor.

In SpinScope, Balancing Module, the SPB procedure is achieved by preparing the SpinScope system for measurement with the 'Original Unbalance' radial button selected as shown in Figure 16, and then triggering the measurement. Measurements are then repeated by adding/adjusting the test mass as discussed above and selecting the appropriate radial button in the Balancing tab. The data from the four measurements are combined to determine the unbalance of the tested machine once the "Calculate" button is clicked as shown in Figure 17. The calculated results can then be used to take corrective action as necessary.



Spindle Speed: 25000 rpm
Speed Uncertainty: 5.00 %
Test Mass: 5.00 grams

● No Reference Signal

4-Run Single Plane Balancing

	Ch. 1	Ch. 2	
● Original Unbalance:	8.757E-013	1.193E-007	(at 23712rpm)
○ Run #1 (Test Mass at 0.00 deg) Unbalance:	0.000E+000	0.000E+000	(at 0rpm)
○ Run #2 (Test Mass at 120.00 deg) Unbalance:	0.000E+000	0.000E+000	(at 0rpm)
○ Run #3 (Test Mass at 240.00 deg) Unbalance:	0.000E+000	0.000E+000	(at 0rpm)

RESULTS: **Balancing Mass = 0.00 grams**
Location = 0 degrees

○ Final Unbalance:	0.000E+000	0.000E+000	(at 0rpm)
○ Results:			

○ Reference Signal

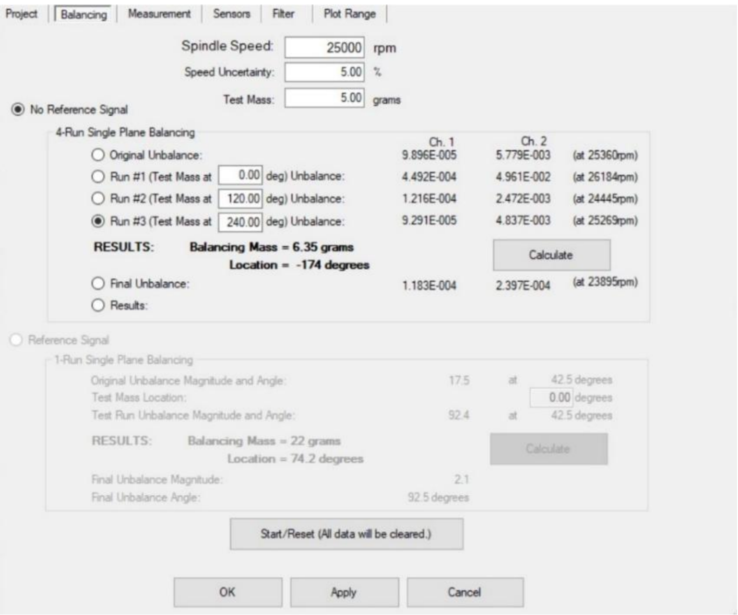
1-Run Single Plane Balancing

Original Unbalance Magnitude and Angle: 17.5 at 42.5 degrees
Test Mass Location: 0.00 degrees
Test Run Unbalance Magnitude and Angle: 92.4 at 42.5 degrees

RESULTS: **Balancing Mass = 22 grams**
Location = 74.2 degrees

Final Unbalance Magnitude: 2.1
Final Unbalance Angle: 92.5 degrees

Figure 16 – Balancing tab in Setup Window.



Spindle Speed: 25000 rpm
Speed Uncertainty: 5.00 %
Test Mass: 5.00 grams

● No Reference Signal

4-Run Single Plane Balancing

	Ch. 1	Ch. 2	
○ Original Unbalance:	9.896E-005	5.779E-003	(at 25360rpm)
○ Run #1 (Test Mass at 0.00 deg) Unbalance:	4.492E-004	4.961E-002	(at 26184rpm)
○ Run #2 (Test Mass at 120.00 deg) Unbalance:	1.216E-004	2.472E-003	(at 24445rpm)
● Run #3 (Test Mass at 240.00 deg) Unbalance:	9.291E-005	4.837E-003	(at 25269rpm)
○ Final Unbalance:	1.183E-004	2.397E-004	(at 23895rpm)

RESULTS: **Balancing Mass = 6.35 grams**
Location = -174 degrees

○ Results:

○ Reference Signal

1-Run Single Plane Balancing

Original Unbalance Magnitude and Angle: 17.5 at 42.5 degrees
Test Mass Location: 0.00 degrees
Test Run Unbalance Magnitude and Angle: 92.4 at 42.5 degrees

RESULTS: Balancing Mass = 22 grams
Location = 74.2 degrees

Final Unbalance Magnitude: 2.1
Final Unbalance Angle: 92.5 degrees

Figure 17 – Balance tab in Setup Window, updated with 4-Run Single Plane Balancing measurements.

2.6 Module 5: Remote Force

The Remote Force Module in SpinScope provides an alternative method of force measurement in situations where direct measurement at the location where the forces are applied is not feasible. In the case of machining forces, for example, direct measurement during machining requires the use of expensive table or rotary dynamometers which may not be applicable in all situations. The idea behind Remote Force Module is to place an accelerometer (or other sensor) at a remote location away from the point where forces are applied, and then to reconstruct the forces from the accelerometer measurement by means of dynamic compensation.

During machining operations, for example, it is not possible to measure cutting forces live by attaching a sensor to the end point of the rotating tool. Remote Force Module attempts to address this issue by measuring the force remotely, for example by placing the accelerometer on the non-rotating spindle head as was done with the Spindle Condition Module during the STI (Strategic Technological Innovation) project number P1001-7-11. Raw measurements obtained from a sensor located in such a way would not be sufficient for determining the cutting forces, because prior experience tap testing with TXF software has demonstrated that tool-holder-spindle assemblies are flexible and have structural dynamics that can resonate (vibrate) at critical frequencies. As a result, the periodic cutting forces applied at the tool tip and transferred through the flexible tool-spindle structure to the remote sensor will be distorted by the FRF of the structure between the tool end point and the remote accelerometer.

Dynamic compensation can be applied to alleviate the resulting distortions. This is achieved by measuring the FRF between the tool point and the sensor with tap tests and then using the measured FRF to create an inverse filter which counteracts the effects of the system's structural dynamics. The process is illustrated in Figure 18 and Figure 19.

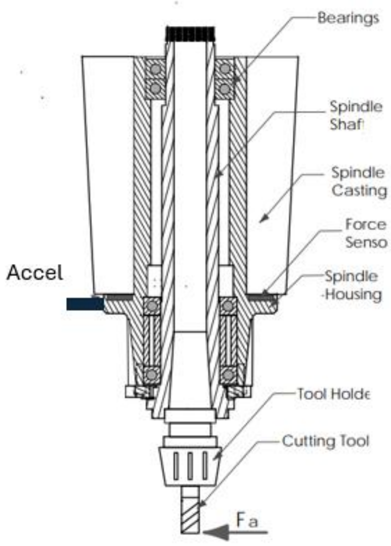


Figure 18 – Example remote force measurement configuration. (Altintas, 2002)

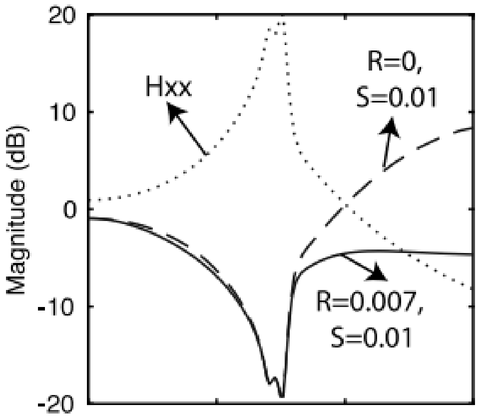
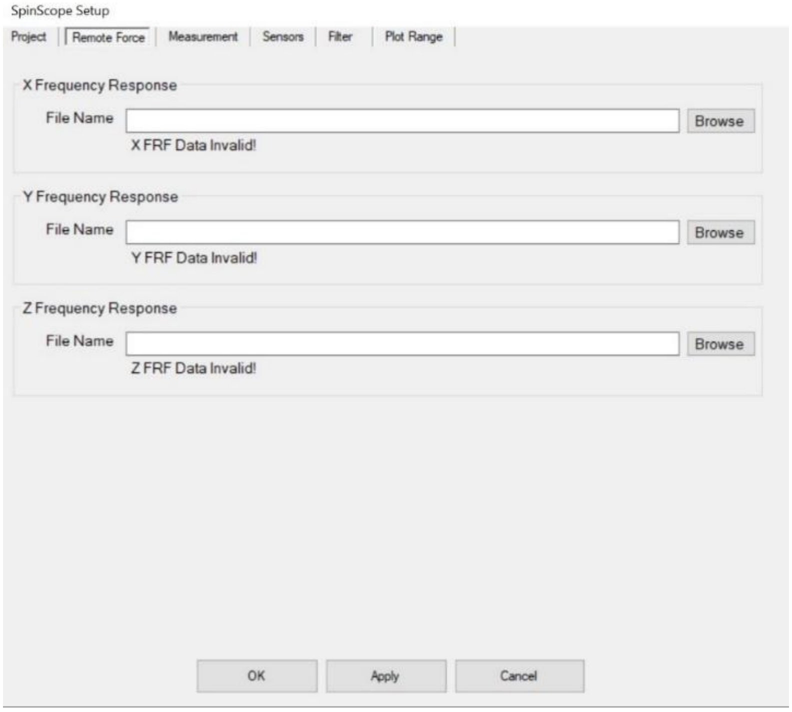


Figure 19 – Measured FRF (dotted line) and compensating inverse filters (solid and dashed lines) for a dynamic system are shown. (Ahmadi, 2002)

Using the Remote Force Module adds the Remote Force tab to the Setup Window as shown in Figure 20. The options in Remote Force tab allow the user to load x, y, and z direction FRF data previously obtained with tap testing. The loaded FRF data is then applied in the Filters tab, which is reproduced in Figure 21. As shown in the figure, using the Remote Force Module adds the Inverse FFT (IFFT) filter to the list of options available in the filter type drop down menus. IFFT filters are available for all three measurement directions. By applying the IFFT filters to the appropriate channels of the DAQ device, dynamic distortion in the remote measurement is compensated when the measurements are triggered in SpinScope.

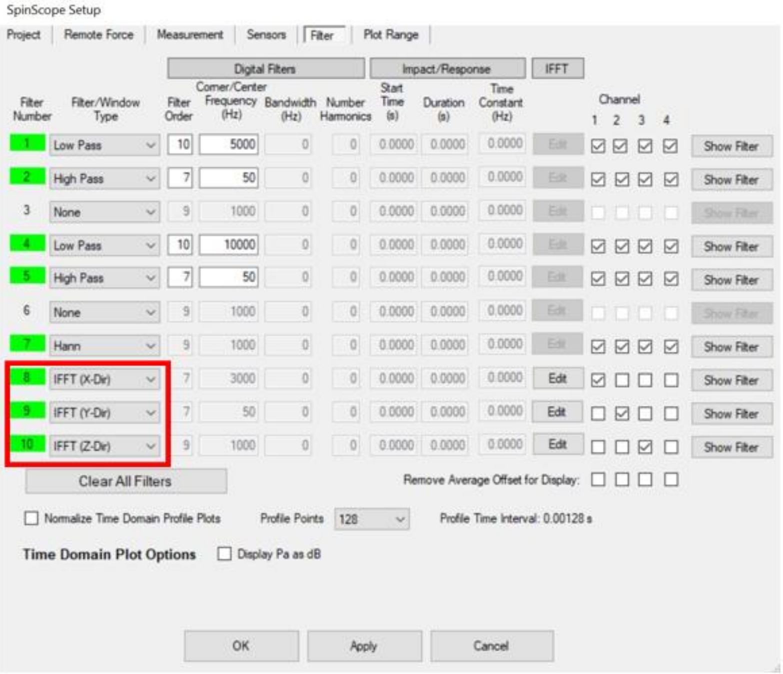


X FRF Data Invalid!

Y FRF Data Invalid!

Z FRF Data Invalid!

Figure 20 – Remote Force tab in Setup window.



Filter Number	Filter/Window Type	Filter Order	Corner/Center Frequency (Hz)	Bandwidth (Hz)	Number Harmonics	Start Time (s)	Duration (s)	Time Constant (Hz)	Channel 1	Channel 2	Channel 3	Channel 4
1	Low Pass	10	5000	0	0	0.0000	0.0000	0.0000	☑	☑	☑	☑
2	High Pass	7	50	0	0	0.0000	0.0000	0.0000	☑	☑	☑	☑
3	None	9	1000	0	0	0.0000	0.0000	0.0000	☐	☐	☐	☐
4	Low Pass	10	10000	0	0	0.0000	0.0000	0.0000	☑	☑	☑	☑
5	High Pass	7	50	0	0	0.0000	0.0000	0.0000	☑	☑	☑	☑
6	None	9	1000	0	0	0.0000	0.0000	0.0000	☐	☐	☐	☐
7	Hann	9	1000	0	0	0.0000	0.0000	0.0000	☑	☑	☑	☑
8	IFFT (X-Dir)	7	3000	0	0	0.0000	0.0000	0.0000	☑	☐	☐	☐
9	IFFT (Y-Dir)	7	50	0	0	0.0000	0.0000	0.0000	☐	☑	☐	☐
10	IFFT (Z-Dir)	9	1000	0	0	0.0000	0.0000	0.0000	☐	☐	☑	☐

Remove Average Offset for Display: ☐ ☐ ☐ ☐

☐ Normalize Time Domain Profile Plots

Profile Points 128

Profile Time Interval: 0.00128 s

Time Domain Plot Options ☐ Display Pa as dB

Figure 21 – Filter tab in Setup Window when the Remote Force Module is used. IFFT filters using x, y, and z direction FRFs is illustrated.

An initial investigation of the module indicates that FRFs used for dynamic compensation must be measured with SpinScope, while FRFs embedded in .txf files cannot be imported into SpinScope. It may be possible to export FRFs from TXF as a text file and then reimport the data into SpinScope, but TXF-measured FRFs that is directly imported into SpinScope cannot be correctly parsed, resulting in invalid data.

When the IFFT filter is properly constructed, however, the Remote Force module of SpinScope can reconstruct the applied force. Figure 22 below shows a ‘naïve’ force measurement, with the measurement signal directly measured with accelerometers reconstructed as a force.

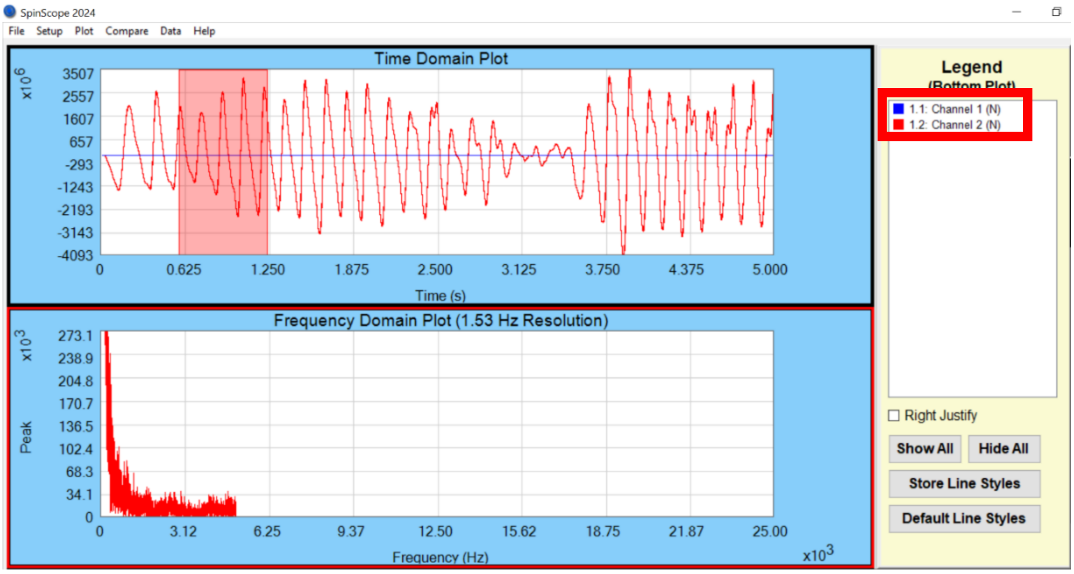


Figure 22 – 'Naive' remote force measurement. Note the units for the measurement signal obtained with accelerometers.

3 Hypothesis

There is no formal hypothesis stated in the project application that can be tested. However, the premise of the project is that value for industry can be derived from at least one module in SpinScope.

Furthermore, it is expected that competency in the use of the SpinScope modules will be obtained that can be extended through further project work at DAMRC.

4 Success Criteria

The project was conceived as a scouting activity and would be considered a success if the following criteria are met:

- Acquire knowledge regarding capabilities, features and operation principles.
- Evaluate through practical tests the effectiveness of each module.
- Identify opportunities to use the software capabilities in the industry.

5 Project Scope/ description

The scope of the project is defined by the following limitations set out in this section. Specifically, the project has been allocated

- 200 project hours
- 80 hours for tap testing
- 15 hours for testing the SpinScope modules in the DMU 80 (or similar CNC machine)
- Budget of DKK 153.175 (excluding VAT)
- A timeline spanning 1 month

Additionally, the investigation of the SpinScope modules will be limited to the features and output already provided by the software, and potential value provided by additional post-processing or analysis will only be highlighted for consideration in future projects. Tests to be conducted in phase 3 will also be limited to what can reasonably be achieved using the DMU 80T machining center available at DAMRC.

6 Risk Analysis

The following risks to the advancement and completion of this project specifically have been identified:

- Planned test activities may be unfeasible to due unforeseen issues with the software. The risk of such an outcome is more likely than not when considering past experiences using additional modules. This risk is mitigated by planning multiple test activities and communicating findings to project management.

- The cost associated with the tools and other materials required for testing may exceed the funding allocated by the project budget. This risk is mitigated by carefully planning test activities to minimize waste and maximise the useful life of the tool.
- The project can be delayed by unintended damage to the tap test equipment. This risk is mitigated by following standard test procedures when using the tap test equipment and by having contingency plans and appropriate insurance in place to mitigate worst-case scenarios.

7 Experiment Design

7.1 Introduction

After a midterm evaluation where the findings of the pre-analysis are reviewed, it is decided to proceed with additional tests focusing on the Balancing and Remote Force modules of SpinScope, with the view of increasing in-house competency for the use cases of these modules. Unless otherwise stated, the required equipment for the test only consists of the contents of the MetalMAX equipment as it pertains to SpinScope software. The proposed test procedures and requirements for achieving this objective are presented in the following subsections.

7.2 Test Design/Process

7.2.1 Balancing

The test procedure for the Balancing module is prescribed by the required workflow of the software, in which a series of acceleration measurements are obtained from unbalanced rotating machinery. Acceleration measurements are obtained both from the natural state of the machine as well as when a test mass is added to induce a state of unbalance. Measurements are repeated with a test mass placed at different locations to thoroughly investigate the unbalance of the machine. The test mass is added by use of a custom flywheel or similar, but several configurations are possible for adding the test mass. An example experimental setup is shown in Figure 23.

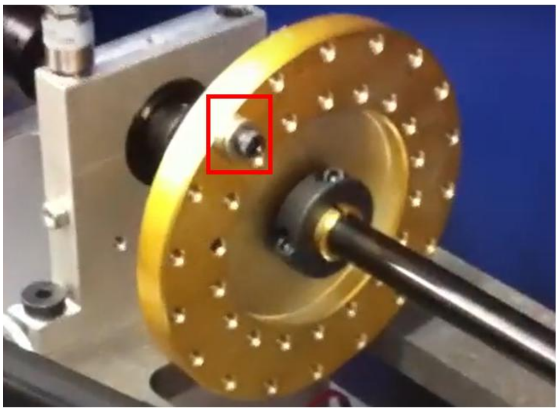


Figure 23 – Example experimental setup for evaluating Balancing module [11]

The procedure for performing the 4-Run Single Plane Balancing test method using SpinScope is as follows:

1. Prepare the SpinScope Software for measurement according to the user manual, securely attach the accelerometer(s) to the machine to be tested.
2. Run the spindle at a predetermined speed. Record the steady state speed in the Balancing tab of SpinScope.
3. In the Balancing tab, ensure that the “Original Unbalance” radial button under “4-Run Single Plane Balancing” heading is selected.
4. Trigger the acceleration measurement. Stop the spindle after measurement is complete.
5. Maintaining the same steady state spindle speed, repeat steps 2-3 for each subsequent “Run #” in the balancing tab while adjusting the location of the test mass. Record the angular position of the test mass in the balancing tab.
6. When all four measurements are obtained, press the calculate button in the Balancing tab to calculate the natural unbalance of the spindle.
7. Add a compensating mass to balance the spindle. Repeat the above test procedure to verify that the spindle is balanced as expected. Record the results.

7.2.2 Remote Force

As discussed in 2.6, the test procedure for the Remote Force module consists of measuring the FRF between the location of an applied force and the remote measuring location, constructing compensating filters in SpinScope, and measuring the force remotely which is then validated against a known reference. Two test processes are designed based on the availability of a dynamometer to directly measure the applied force.

The availability of a dynamometer simplifies the direct force measurement necessary for validating the results obtained with Remote Force module. In this case, the FRF measured between the tool point and spindle head in a machining center can be applied in a series of cutting tests to measure the machining forces remotely, which are simultaneously measured directly with the dynamometer, as shown in Figure 24. The test procedure would then be as follows:

1. Prepare the SpinScope Software for measurement according to the user manual, securely attach the accelerometer(s) to the remote measurement location.
2. Measure any of the FRFs in X, Y, and Z tool direction, as needed, using the Frequency Response module of SpinScope. Save the FRF data.
3. In a new SpinScope file using Remote Force module, load the FRF data measured in step 2 and apply the relevant IFFT filters in the Relevant tabs of the setup window in SpinScope.
4. Prepare the workspace of the CNC machine for machining, leaving the accelerometers from step 2 in place. Install the dynamometer below the workpiece to be machined during testing.
5. Perform cutting tests, measuring the resulting forces with both the remote accelerometer and the dynamometer simultaneously.

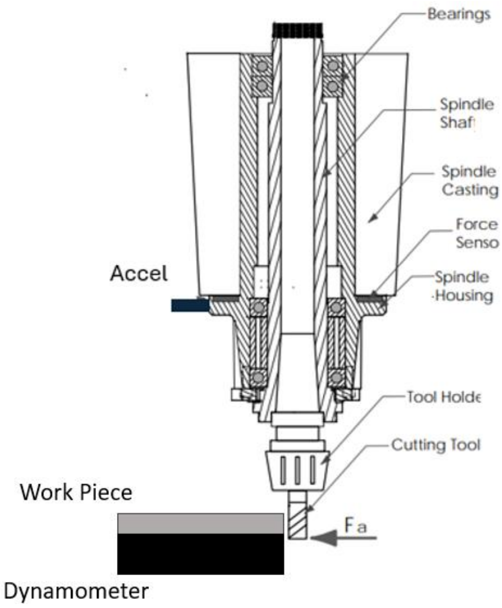


Figure 24 – Proposed experimental setup for evaluating Remote Force module.

The above test procedure is intuitive and easy to apply, however, it is reliant on a third-party measurement system (the dynamometer). An alternative test procedure which requires only the material available in the MetalMax equipment is possible by adapting the procedures in the MetalMax documentation for calibrating the impact hammers and accelerometers. The calibration procedure is used to check the calibration of the sensors if some deviation from factory calibration has occurred and involves recording the input and output signals of a known system and comparing the results against expected values. The known system in this case is the 1 kg test mass (shown in Figure 25) which is included in the MetalMAX equipment. More information about the calibration procedure can be found in MetalMAX TXF 2011 user manual (MetalMAX).

A test process for evaluating the Remote Force module based on the above calibration procedure would be as follows:

1. Suspend the test mass as shown in Figure 25. Attach an accelerometer to one end of the test mass.
2. Prepare the SpinScope software for measurement and measure the FRF of the test mass using the Frequency Response module. Save the resulting data.
3. In a new SpinScope file, load the FRF data from step 2. Construct the relevant IFFT filter and apply it to accelerometer signal, so that one accelerometer measures remote force and the other measures acceleration.
4. While applying a force to the test mass, measure the resulting acceleration and remote force with SpinScope.
5. Use the acceleration signal and known test mass to calculate the theoretically expected force and compare with the measured remote force.

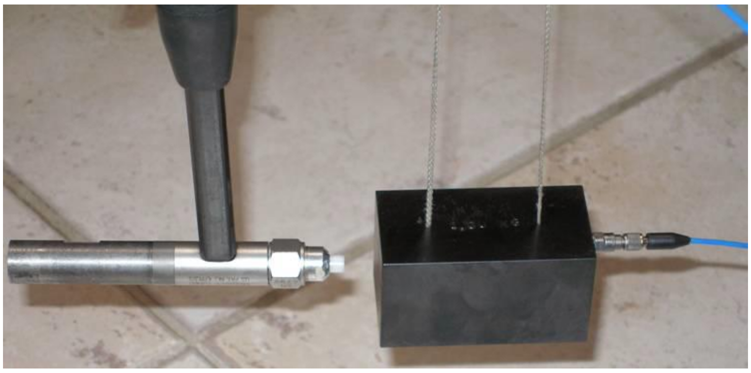


Figure 25 – The calibration mass used to verify the calibration/sensitivities of the hammer and accelerometer.

7.3 Test Material

7.3.1 Balancing Module

Since the designed test for the Balancing Module requires only to measure acceleration signals during the SPB procedure, it is not necessary to consume any material during testing. Machining for the Balancing Module test is then limited to the preparation of a custom experimental workpiece with which to test various unbalance as shown in Figure 23. However, since only eighty machining hours are allocated to the project, and since it is expected that most of these hours would be used in the tests of the Remote Force Module, an experimental setup is made using existing components available at DAMRC.

To this end, the workpiece shown in Figure 26, which has already been machined, is used in the proposed tests of the Balancing Module. The threaded holes in the part can then be used in conjunction with spare screws, washers, etc, to add a test mass for the SPB procedures as illustrated in Figure 23.

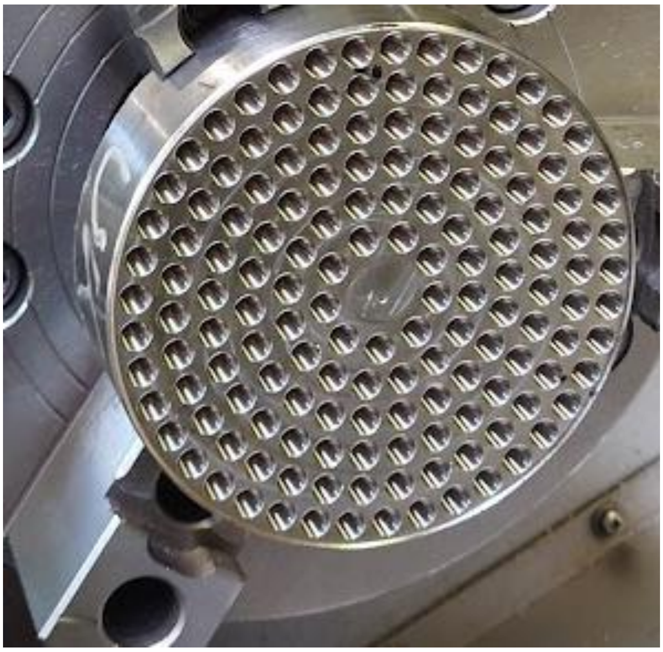


Figure 26 – The co-opted workpiece to be used in Balancing Module tests.

7.3.2 Remote Force

In the case where a dynamometer is used for the Remote Force Module tests, it is proposed that any easy to machine, rectangular stock available at DAMRC be used for the cutting tests. In addition to this, it will be necessary to machine adapter mounting plates to securely fasten both the dynamometer and the workpiece to the table of the CNC machine.

In the case where a dynamometer is not used, the calibration mass included in the MetalMAX equipment will be used, in which case, additional material will not be necessary for testing.

7.4 Conducting the tests

7.4.1 Balancing Module

From the project application, it is expected that tests of the SpinScope modules will involve tests on the DMU machining center. However, in the interest of conducting the tests in an economical manner, the Balancing module will be evaluated with tests involving the workpiece shown in Figure 26 mounted in the Mazak QuickTurn Turning Center. Additional tests involving the DMU machining center may be conducted later if there are sufficient hours available for the project.

7.4.2 Remote Force

It is expected that tests of the Remote Force module incorporating a dynamometer can be conducted in the DMU machining center as prescribed in the project application. However, the specific dynamometer model to be used has not been specified. Consequently, the exact method and machines used is subject to change to facilitate the experiment. If a dynamometer is not available for use, a variation of the second test procedure given in 7.2.2 will be applied.

8 Test Results

8.1 Introduction

As discussed in section 7, it was decided during the midterm review to proceed with tests of the Balancing and Remote Force Modules. Of the two modules, initial emphasis is to be placed on the Balancing Module until a dynamometer can be sourced for the tests of the Remote Force Module. Since then, a modified procedure for the Remote Force module was adopted to expedite testing. The new procedure consists of

1. Measuring the tool-tool holder cross FRF using SpinScope.
2. Prepare the SpinScope software for measuring Remote Force by loading the cross-FRF data and applying the relevant IFFT filters.
3. Apply a remote force using the instrumented impact hammer from the other MetalMax equipment and compare the results with the force directly measured with the impact hammer.

8.2 Balancing Module

Evaluating the Balancing Module according to the procedures of 7.2.2 is achieved by mounting the test piece in the Mazak QuickTurn as shown in Figure 26 and following the relevant test procedures described above. The “Extra Large” accelerometer from the MetalMax equipment (PCB model nr.

393A03) and the accelerometer from the TPI Inc. Smart Meter (model nr. A9012) are mounted to the non-rotating spindle head of the Mazak QuickTurn as shown in Figure 27.

A reference datum specifying the 0 degrees and gradients signifying angular position is marked on the test workpiece, with positive angular positions oriented clockwise around the workpiece. The SPB procedure is applied testing various configurations consisting of the natural unbalance of the machine with the mounted workpiece, and when an unbalance is induced by installing a screw with washers into one of the threaded holes. The test mass used in the 4-Run SPB procedure is added in the same manner, as shown in Figure 28. For all configurations, the test mass and mass simulating unbalance are placed at approximately 50 mm from the center. For all configurations involving a simulated unbalance, the added mass is placed at a position of 270 degrees.

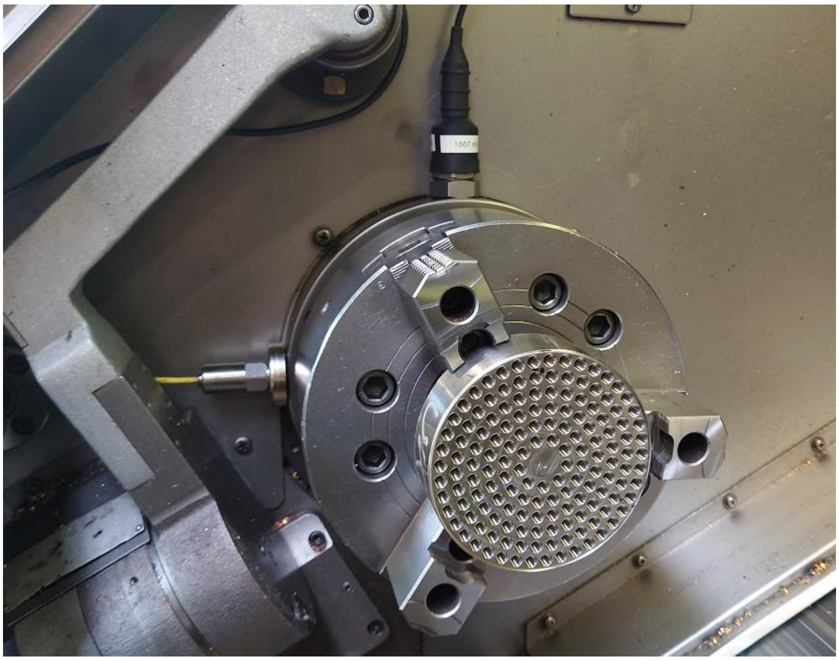


Figure 27 – Accelerometer placement in the Mazak QuickTurn.

Many of the tested configurations described above either failed to induce a meaningful unbalance, miscalculated the required corrective mass, or demonstrated poor repeatability. Reasonable results were obtained for one trial of the 4-Run SPB procedure in SpinScope, in which the spindle speed of the lathe was set to 3000 RPM (the maximum achievable by the machine), the mass simulating unbalance was 20.02 grams, and the test mass for the 4-Run SPB was 30.92 grams. Acceleration signals were measured from two channels at a sampling frequency of 100.000 Hz for 5 seconds, and the FFT window length was set to 1.048.576 to envelop the entire measurement period. The resulting unbalance measured before and after correction is presented in Table 1.

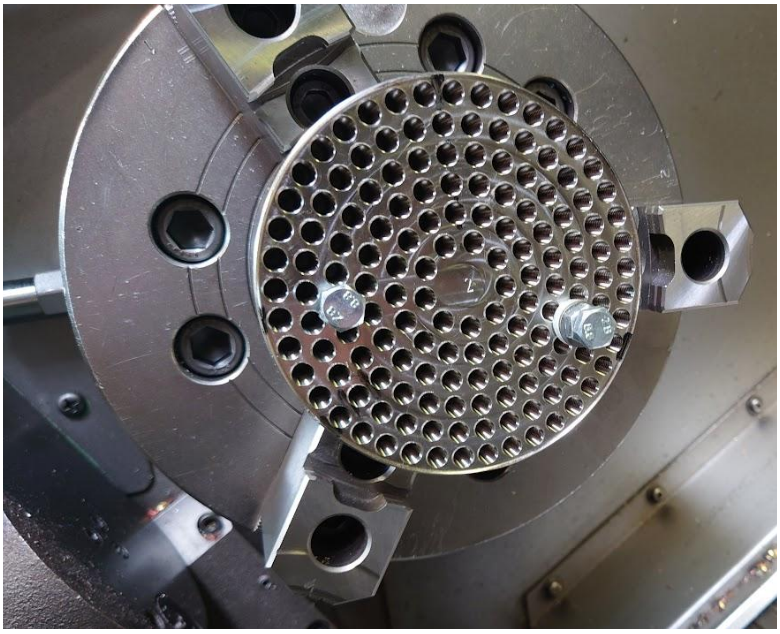


Figure 28 – Workpiece with screws simulating unbalance and test mass per 4-Run SPB procedure.

Parameter	Channel 1 [g*mm]	Channel 2 [g*mm]
Original Unbalance	0.119	0.00
Run Nr.1 (Test mass at 0 degrees)	0.128	0.00
Run Nr.2 (Test mass at 120 degrees)	0.059	0.00
Run Nr.3 (Test mass at 235 degrees)	0.128	0.00
Results of SPB Calculations	Balancing Mass: 60.40 grams Location: 95 degrees	
Final Unbalance (after Applying Correction)	0.014	0.00
Results:	Unbalance changed from 0.12 to 0.01	

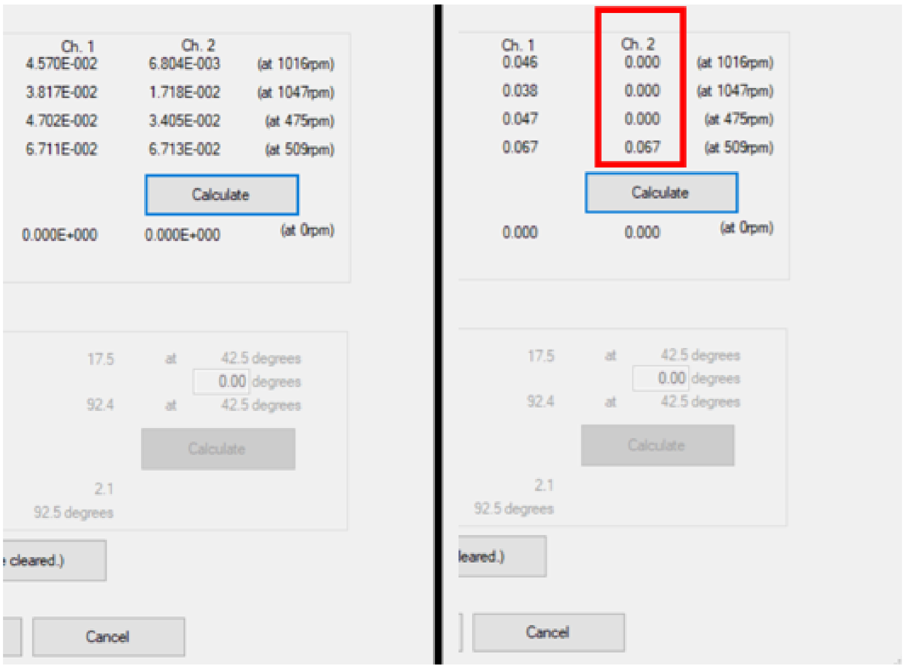
Table 1 – Results of the test of the Balancing Module of SpinScope.

The results in Table 1 indicate that applying the corrective mass as indicated results in a near ten-fold reduction in the unbalance of the lathe spindle, which is expected since the prescribed location of 95 degrees places the corrective mass almost opposite of the ‘simulation’ mass located at 270 degrees. Note that the lack of units for unbalance in Table 1 reflects the quality of the results obtained from SpinScope.

The results in the table indicate that data from channel 2 was not captured. This could be due to either the accelerometer used for channel 2 was faulty, or else the data recorded from that channel is discarded and only channel 1 data is necessary. The possibility of a faulty accelerometer can be neglected, however.

Figure 29 shows data obtained from a different trial than that shown in Table 1 before and after saving and reopening the file. The figure shows that data is successfully obtained from channel 2 during testing. However, this data is lost upon reopening the SpinScope file. This can indicate either that the data is deliberately discarded, or that a software issue with SpinScope is responsible for the loss of data.

Of these possibilities, it is assumed that software issues with SpinScope is the more likely issue. Figure 30 shows an error message that is generated when calculating the required corrective mass and location when using the 4-Run SPB procedure in SpinScope. This error message was generated when the “Calculate” button in the figure was clicked as part of the workflow for using the Balancing module in SpinScope after recording acceleration data for different locations of the test mass. The error message appeared without any deviation in the general test procedure, and it is unclear why this error appears inconsistently. It is surmised that software issues, i.e. bugs or glitches, cause this and other problems encountered when using the software.

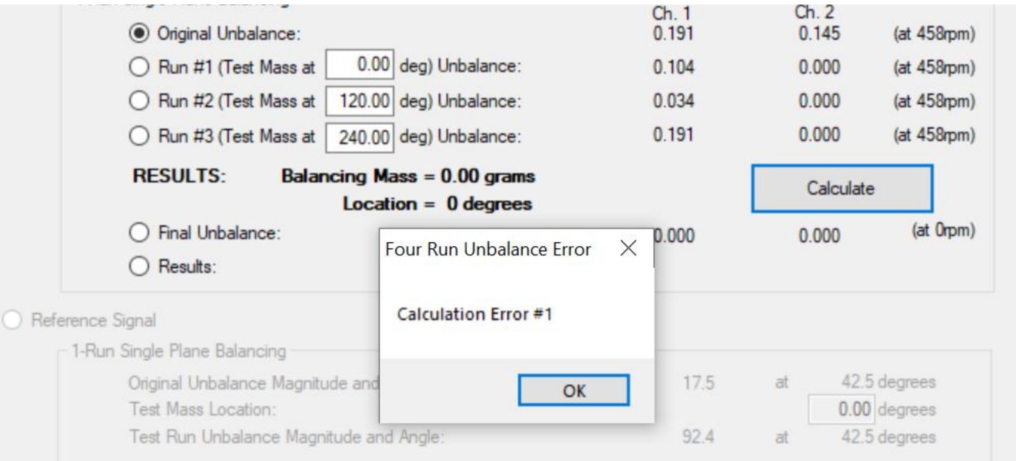


Ch. 1	Ch. 2	
4.570E-002	6.804E-003	(at 1016rpm)
3.817E-002	1.718E-002	(at 1047rpm)
4.702E-002	3.405E-002	(at 475rpm)
6.711E-002	6.713E-002	(at 509rpm)
0.000E+000	0.000E+000	(at 0rpm)

Ch. 1	Ch. 2	
0.046	0.000	(at 1016rpm)
0.038	0.000	(at 1047rpm)
0.047	0.000	(at 475rpm)
0.067	0.067	(at 509rpm)
0.000	0.000	(at 0rpm)

17.5 at 42.5 degrees
0.00 degrees
92.4 at 42.5 degrees
2.1
92.5 degrees

Figure 29 – Unbalance measured from channels 1 and 2 before (left) and after (right) reopening the SpinScope file. Note the lack of channel 2 data after reopening the file.



	Ch. 1	Ch. 2	
● Original Unbalance:	0.191	0.145	(at 458rpm)
○ Run #1 (Test Mass at 0.00 deg) Unbalance:	0.104	0.000	(at 458rpm)
○ Run #2 (Test Mass at 120.00 deg) Unbalance:	0.034	0.000	(at 458rpm)
○ Run #3 (Test Mass at 240.00 deg) Unbalance:	0.191	0.000	(at 458rpm)
○ Final Unbalance:	0.000	0.000	(at 0rpm)

RESULTS: **Balancing Mass = 0.00 grams**
Location = 0 degrees

○ Results:

Four Run Unbalance Error

Calculation Error #1

○ Reference Signal

1-Run Single Plane Balancing

Original Unbalance Magnitude and 17.5 at 42.5 degrees
Test Mass Location: 0.00 degrees
Test Run Unbalance Magnitude and Angle: 92.4 at 42.5 degrees

Figure 30 – An unexpected calculation error occurs even after recording all required measurements.

Follow-up tests of the Balancing module were performed on the DMU machining center due to a Mazak QuickTurn machining center breakdown. The test piece used previously was machined so that it could be accommodated by the HSK spindle of the DMU machining center and tool holder as shown in Figure 33.

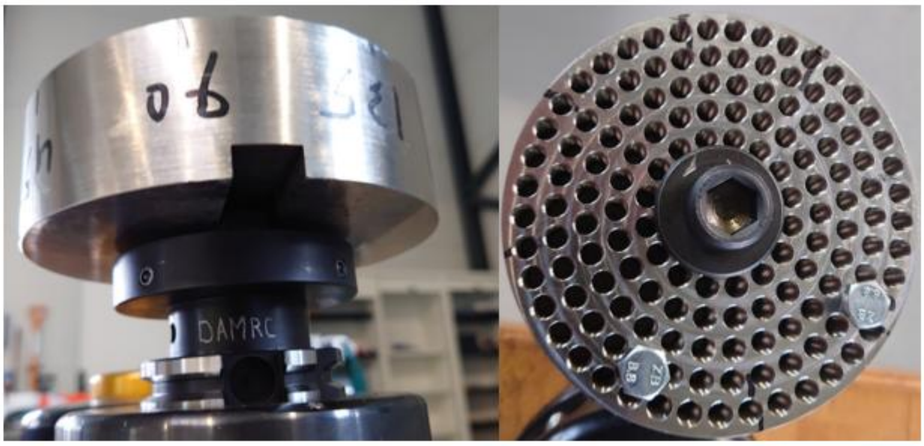


Figure 31 – The test piece in Figure 27 as modiifed for testing in the DMU.

The modified workpiece is installed in the DMU machining center, and the Balancing module is retested using the same procedure used with the Mazak, with the difference that only one accelerometer measurement is used and the resulting acceleration from the imbalance is also recorded with SmartMeter.

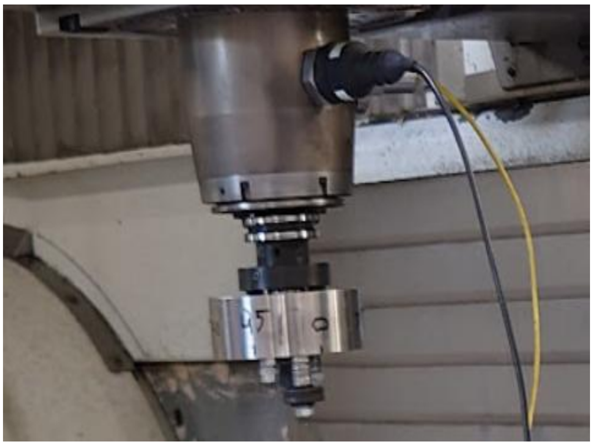


Figure 32 – Test configuration for evaluating the Balancing module with the DMU machining center.

Tests of the Balancing module were performed according to the procedure in 7.2.1 for three configurations: no unbalance mass added to the DMU spindle, and the unbalance mass located at 45° and then 180° with respect to an arbitrary reference. The spindle speed for all tests is 3000 RPM. The mass used to induce an unbalance is approximately twenty grams, while the test mass used for the SPB balancing procedure is approximately thirty grams.

The results obtained by the Balancing Module when the unbalance mass is located at 45° are presented in Table 2,which indicates that elevated unbalance and acceleration was measured during run nr. 1 and 2 compared to nr. 3 and the original unbalance. This suggests that the location of the test mass during run nr. 3 would be ideal for a corrective mass to balance the spindle, which is logical given the location of the unbalance mass. However, the Balancing module of SpinScope recommended balancing mass located at 22 degrees which, as shown in the table, exacerbated the preexisting unbalance.

Parameter	MetalMax Balancing [g*mm]	SmartMeter [G's]
Original Unbalance	0.118	1.397
Run Nr.1 (Test mass at 0 degrees)	0.332	2.772
Run Nr.2 (Test mass at 125 degrees)	0.302	2.244
Run Nr.3 (Test mass at 225 degrees)	0.119	1.634
Results of SPB Calculations	Balancing Mass: 100.26 grams Location: 22 degrees	
Final Unbalance (after Applying Correction)	0.914	1.440
Results:	Unbalance changed from 0.12 to 0.91	

Table 2 – DMU Balancing Test with unbalance mass at 45°.

The balancing test is repeated with no additional mass added to the test piece, the results of which are presented in Table 3. The results indicate that the measured unbalance is relatively minor during the first run, which is reflected the resulting recommendation of placing a balancing mass at -7 degrees. Following the recommendations obtained with SpinScope results in the original unbalance of 0.04 g*mm being reduced by 0.01 g*mm, or 25%.

Parameter	MetalMax Balancing [g*mm]	SmartMeter [G's]
Original Unbalance	0.04	1.844
Run Nr.1 (Test mass at 0 degrees)	0.194	1.609
Run Nr.2 (Test mass at 125 degrees)	0.281	1.962
Run Nr.3 (Test mass at 225 degrees)	0.271	1.760
Results of SPB Calculations	Balancing Mass: 10.38 grams Location: -7 degrees	
Final Unbalance (after Applying Correction)	0.03	1.369
Results:	Unbalance changed from 0.04 to 0.03	

Table 3 – DMU Balancing Test with no unbalance mass.

The results of the third test of the Balancing module using the DMU is presented in Table 4, which similarly reports reduced unbalance during run nr. 1. However, the difference in the third test is more significant, with the unbalance in the second and third run being approximately fifteen times greater than the unbalance in the first run, compared to approximately 1.5 times greater in the second test. Implementing the recommendation to place a balancing mass at -1° results in a 10-times reduction in the original unbalance, as shown in the last row of the table.

Parameter	MetalMax Balancing [g*mm]	SmartMeter [G's]
Original Unbalance	0.201	1.495
Run Nr.1 (Test mass at 0 degrees)	0.029	2.274
Run Nr.2 (Test mass at 125 degrees)	0.436	2.051
Run Nr.3 (Test mass at 225 degrees)	0.430	2.255
Results of SPB Calculations	Balancing Mass: 24.24 grams Location: -1 degrees	

Final Unbalance (after Applying Correction)	0.012	1.395
Results:	Unbalance changed from 0.12 to 0.01	

Table 4 – DMU Balancing Test with mass at 180°.

8.3 Remote Force

To evaluate the Remote Force module of SpinScope, the test method outlined in section 8 to obtain reconstructed forces using an IFFT filter. The Frequency Response module of SpinScope is used to obtain the FRF between the small accelerometer (model nr. 352C23) placed at the tool center point (TCP) of the ‘small’ KUKA robot (KR 10 R900) and a remote impact location as shown in Figure 33. Then, an impact is applied at the same impact location with an instrumented hammer and the response measurement at the TCP is used with the Remote Force module to reconstruct the remote force. The reconstructed remote force is compared with the applied force as measured by the impact hammer.

Limitations in the SpinScope software make it impossible to simultaneously measure the force applied by the impact hammer and reconstruct the force from the response measurement. Therefore, the 2022 version of TXF software is used to measure the applied force while the 2024 version of SpinScope is used to reconstruct the remote force.

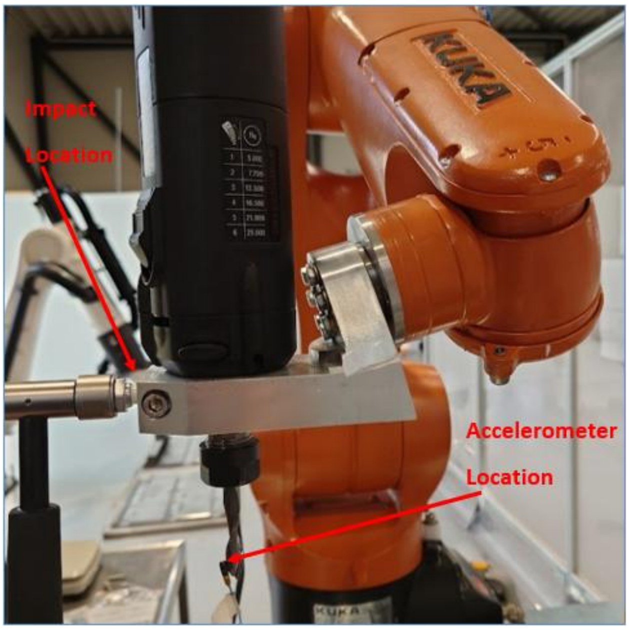


Figure 33 – Impact and response measurement location on the KUKA robot (KR 10 R900)

Seven hammer impacts are measured with TXF and reconstructed with SpinScope; for brevity, the results obtained with one impact are presented below as similar results are obtained for all impacts.

The impact force measured with TXF is presented in Figure 34, which exhibits a maximal value of approximately 215 N, while the reconstructed impact is shown in Figure 35. The reconstructed impact, by comparison, has a maximal value of approximately 204 N, representing a relative error of 5.11% with respect to the impact measured with TXF.

The reconstructed force also exhibits low frequency ringing after the impact, which can be characterised as an artifact of the raw measurement obtained with the accelerometer. The results presented below are obtained while only using the applicable IFFT filters, and it is expected that the erroneous ringing in the reconstructed force can be mitigated by applying additional filters in the filter tab of the SpinScope software. It was also observed during testing that accelerometer measurements must be within the FFT window of SpinScope for the IFFT filter and force reconstruction to be properly applied.

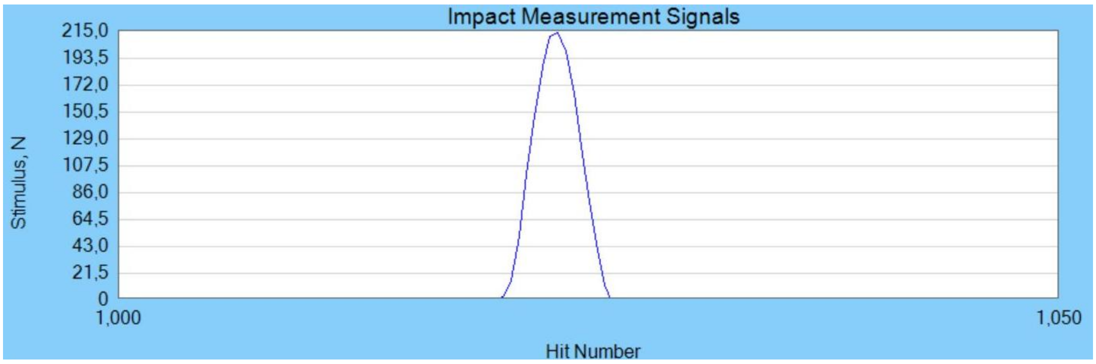


Figure 34 – Hammer impact measured with TXF. The force has a maximum value of approximately 215 N.

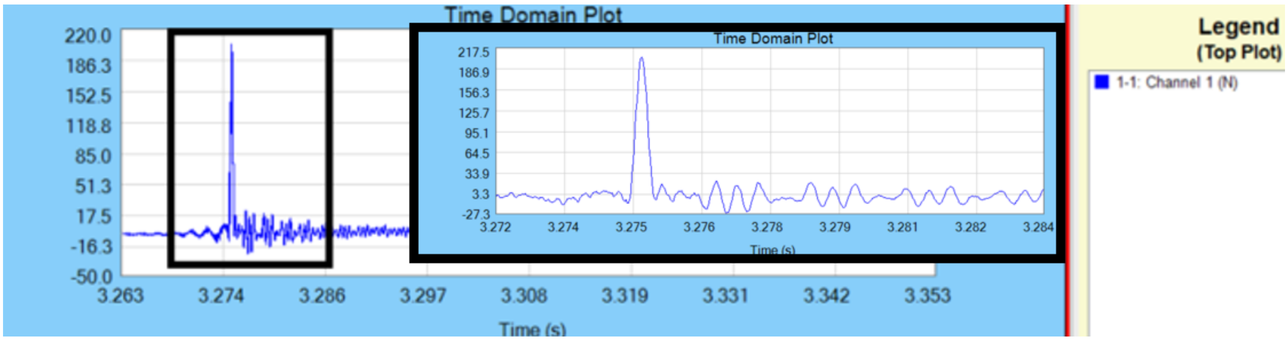


Figure 35 – SpinScope reconstruction of the hammer impact in Figure 34 using Remote Force module and the accelerometer at the robot TCP. The reconstructed force has a maximum value of approximately 204 N.

Successfully reconstructing the remote impact with a relative error on the order of 5% validates the premise stated in section 2.6 regarding the use of the Remote Force Module. While the remote force was applied at the spindle flange of the robot and reconstructed with accelerometer measurement at the TCP, it is expected that the same results can be obtained while inverting the location of the accelerometer and impact. By doing so, the FRF of the structure is measured while applying hammer impacts at the TCP and measuring the response at the spindle flange. Forces applied at the tool can then be reconstructed by the remotely placed accelerometer, which can be used to reconstruct cutting forces during machining processes.

8.4 Partial conclusion

Practical tests of the Balancing and Remote Force modules of SpinScope were carried out on a KR 10 R900 robot arm, the Mazak Quick Turning Center, and the DMU 80T machining center to evaluate their capabilities. The experience gained during these tests resulted in a better understanding of the modules and potential next steps. It was observed during these tests that the Balancing module, while intuitive and easy to use, resulted in inconsistent results and was prone to issues in the MetalMax software. The Remote Force module, on the other hand, yielded consistent results but required a more advanced understanding of tap testing and frequency analysis.

It was also observed that the use of both modules would be subject to the same problems encountered when using SpinScope in general, namely that access to the workspace of the machine to be tested must be achieved. Furthermore, additional challenges exist for the Balancing module, since it is required to attach a test mass to run the SPB procedure which would potentially require a custom test piece for each spindle to be tested in a given project. It is therefore recommended that Remote Force, but not Balancing, module be considered for additional development considering the relative strength of the respective business cases.

9 Discussion

The application for this project calls for the new modules in SpinScope to be investigated for new opportunities to benefit Danish industry, including testing on the DMU 80T machining center. Considering the accelerated nature of this project (1 month, 200 hours), the features of all the modules are documented (in the pre-analysis section of this report) and only selected modules are tested.

Testing the Balancing module requires installing a test mass in the spindle of interest at various angular locations, complicating the process of testing with the DMU 80T. As a result, testing was done on the Mazak Quick Turn machining center using pre-existing test pieces to facilitate the testing process. The test piece was later machined for tests with the DMU 80T following technical issues with the Mazak Quick Turn.

The remote Force module, in comparison, was conducted on the KUKA robot while tap tests for the Robotic Machining project were already underway to further compress the length of the project. This was possible as the Remote Force module does not require additional test masses, unlike the Balancing module, needing only FRF data previously measured with tap testing.

10 Conclusion

After an initial screening of the features in the new version of SpinScope, two of the available modules, Balancing and Remote Force, were tested internally to evaluate their capabilities and identify potential business cases. The results demonstrated that Remote Force module, when used correctly, could reconstruct unknown forces with a relative error on the order of 5% by measuring the cross-FRF between the location of the applied force and the accelerometer used for remote measurement. The Balancing module, by contrast, produced inconsistent results and was affected by software glitches, but was intuitive to use.

From the activities of this project, the features and capabilities of all the new software modules were documented, and standard operating procedures were generated for the two modules that were extensively tested. The project is therefore a success as the stated success criteria of “understanding of function and difference between the newly acquired modules” has been achieved.

Considering the experience gained using the SpinScope during this and other projects, competency using the various modules has been acquired and the software should be used to assist future projects were applicable. It is also strongly recommended that DAMRC capabilities using the Remote Force module be matured in a future R&D project, since the capability of indirectly measuring machining forces without the need for the cumbersome fixtures used with table dynamometers is of particular interest to Danish industry.

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