Time Histories for IEEE693 Testing and Analysis: A Summary of Unfiltered and Filtered Versions

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ABSTRACT

This study was undertaken to address new developments in IEEE P693/D16 (IEEE693 WG, 2017) and to account for the new strong motion records from recent major earthquakes and assess their effects on the spectral demand. A large set of both crustal and subduction type records was investigated based on a number of parameters and intensity measures. The best candidates were selected as seed motions. The motions were matched to the IEEE693 spectrum in a time domain at 5% damping which follows the guidelines in IEEE P693/D16 (IEEE693 WG, 2017). In addition, three three-component synthetic time histories were generated. All modified and generated time histories were arranged into a suite of time histories and were proposed for use in the IEEE693 seismic qualification analysis and testing. The suite consisted of four IEEE693-spectrum-compatible time histories modified from crustal records, one IEEE693-spectrum-compatible time history modified from a subduction record, and three IEEE693-spectrum-compatible synthetic time histories. The spectral matching was conducted with a tight tolerance in order to remain within a 15% strip above the IEEE693 spectra in a wide frequency range. The filtered versions of the time histories were also developed to meet limitations of the most of the shaking tables worldwide.

Keywords: ***IEEE693, seismic qualification testing, seismic qualification analysis, spectral matching, filtered versions.***

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DISCLAIMER

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect those of the University of California, Berkeley.

CONTENTS

ABSTRACT I

ACKNOWLEDGMENTS II

DISCLAIMER III

CONTENTS IV

LIST OF FIGURES V

LIST OF TABLES VI

1 INTRODUCTION 1

2 TIME HISTORIES FOR SEISMIC QUALIFICATION TESTING AND ANALYSIS 1

2.1 IEEE693-spectrum-compatible Time Histories Generated from Seed Motions 2

2.2 IEEE693-spectrum-compatible Synthetic Time Histories 2

2.3 Resultant IEEE693-spectrum-compatible Time Histories 3

3 FILTERED VERSIONS OF TESTQKE4IEEE5 25

4 CONCLUSIONS 29

5 REFERENCES 30

APPENDIX A: PLOTS OF UNFILTERED TIME HISTORIES: ACCELERATION, VELOCITY, DISPLACEMENT AND SPECTRA 31

APPENDIX B: PLOTS OF FILTERED TIME HISTORIES: ACCELERATION, VELOCITY, DISPLACEMENT AND SPECTRA 32

LIST OF FIGURES

Figure 2-1. Spectra of synthetic time history (SQ-009.acc) before and after subsequent matching in a time domain by RspMatch09 3
Figure 2-2. IEEE693-spectrum-compatible time history matched to IEEE693 spectrum at 5% damping (TestQke4IEEE5-1 matched from 1940 El-Centro seed record) 5
Figure 2-3. Variation of the Power Spectral Density in time (TestQke4IEEE5-1) 6
Figure 2-4. IEEE693-spectrum-compatible time history matched to IEEE693 spectrum at 5% damping (TestQke4IEEE5-2 matched from 1992 Landers seed record) 7
Figure 2-5. Variation of the Power Spectral Density in time (TestQke4IEEE5-2) 8
Figure 2-6. IEEE693-spectrum-compatible time history matched to IEEE693 spectrum at 5% damping (TestQke4IEEE5-3 matched from 1999 Chi-Chi seed record) 9
Figure 2-7. Variation of the Power Spectral Density in time (TestQke4IEEE5-3) 10
Figure 2-8. IEEE693-spectrum-compatible time history matched to IEEE693 spectrum at 5% damping (TestQke4IEEE5-4 matched from 2010 El Mayor-Cucapah seed record) 11
Figure 2-9. Variation of the Power Spectral Density in time (TestQke4IEEE5-4) 12
Figure 2-10. IEEE693-spectrum-compatible time history matched to IEEE693 spectrum at 5% damping (TestQke4IEEE5-5 matched from subduction seed record) 13
Figure 2-11. Variation of the Power Spectral Density in time (TestQke4IEEE5-5) 14
Figure 2-12. IEEE693-spectrum-compatible time history matched to IEEE693 spectrum at 5% damping (TestQke4IEEE5-6, synthetic) 15
Figure 2-13. Variation of the Power Spectral Density in time (TestQke4IEEE5-6) 16
Figure 2-14. IEEE693-spectrum-compatible time history matched to IEEE693 spectrum at 5% damping (TestQke4IEEE5-7, synthetic) 17
Figure 2-15. Variation of the Power Spectral Density in time (TestQke4IEEE5-7) 18
Figure 2-16. IEEE693-spectrum-compatible time history matched to IEEE693 spectrum at 5% damping (TestQke4IEEE5-8, synthetic) 19
Figure 2-17. Variation of the Power Spectral Density in time (TestQke4IEEE5-8) 20
Figure 2-18. The resultant time histories have spectra closely enveloping the IEEE693 from 0.13 Hz to 33.3 Hz 21
Figure 2-19. Major parameters of the IEEE693-spectrum-compatible time histories 23
Figure 2-20. Number of cycles in the 5%-damped SDOF response (magenta is a threshold specified in IEEE Std 693-2005 (IEEE, 2005) 24
Figure 3-1. Summary of the displacement limitations of shaking tables worldwide 26
Figure 3-2. Percentage of the major shaking tables within certain limitation groups 27

LIST OF TABLES

Table 2-1. List of IEEE693-spectrum-compatible time histories developed in the study 3
Table 3-1. A world list of 3D and 6D shaking tables and 1D shaking tables with long stroke 25
Table 3-2. List of IEEE693-spectrum-compatible time histories filtered to meet limitations of majority of shaking tables 28

1 Introduction

A study conducted earlier on a number of strong motions (Takhirov et al, 2005) resulted in the development of a three-component strong motion called TestQke4IEEE. Based on a detailed analysis, the best candidate was selected from a large set of the strong motions. TestQke4IEEE was developed from a historic record obtained during the 1992 Landers earthquake by matching its spectra to the current IEEE Std 693-2005 (IEEE, 2005) spectra at 2% critical damping. The spectral matching was performed in a time domain, and as a result, the TestQke4IEEE spectra closely matched the IEEE Std 693-2005 (IEEE, 2005) spectra starting at about 0.3Hz. For more than a decade the strong motion had been successfully used for seismic qualification testing and analysis. This study was undertaken to address new developments in the IEEE P693/D16 (IEEE693 WG, 2017) and to account for the new strong motion records from recent major earthquakes, and assess their effects on the spectral demand. IEEE P693/D16 (IEEE693 WG, 2017) is the most recent draft of the next version of the recommended practice. The requirements for development of input time histories for use in shake table testing and analysis given in IEEE P693/D16 (IEEE693 WG, 2017) are very similar to those given in IEEE Std 693-2005 (IEEE, 2005) In P693/D16, spectral matching is to be performed at 5% instead of 2% damping, the high cycle count requirement has been eliminated, and intermediate checks against enveloping tolerance bands have been eliminated. IEEE P693/D16 (IEEE693 WG, 2017) also describes the requirements for the design, analysis and testing of seismic protective devices and equipment/device systems. Such protected systems are required in IEEE P693/D16 (IEEE693 WG, 2017) to be subjected to multiple spectrum-compatible histories when those systems are qualified by analysis. In addition, the filtered versions of the time histories were also developed to meet limitations of the most of the shaking tables worldwide.

2 Time Histories for Seismic Qualification Testing and Analysis

This section summarizes the newly developed time histories for seismic qualification testing and analysis, see (Takhirov et al, 2017a and Takhirov et al, 2017c) for more details. The spectra of the time histories are tightly matched to the IEEE693 spectra at 5% of critical damping. This tight matching was achieved for a wide range of frequencies from 0.13 Hz to 33.3 Hz. Since the spectral accelerations meet and exceed the IEEE693 spectra at low frequencies, they can be used for testing and analysis of seismically isolated equipment. Four time histories were developed from historic records (seed motions) obtained during crustal earthquakes by spectral matching in a time domain. In addition, one time history was derived from a historic record obtained during a subduction type earthquake. In addition, three synthetic time histories matched to the same spectrum were generated to complete the suite of time histories.

2.1 IEEE693-SPECTRUM-COMPATIBLE TIME HISTORIES GENERATED FROM SEED MOTIONS

To preserve the non-stationary feature of the historic seed records, the spectral matching procedure was performed in a time domain. The matching procedure is a FORTRAN implementation of the algorithm developed by Abrahamson (Abrahamson, 1992), RspMatch. It is worth noting that the TestQke4IEEE (Takhirov el al, 2005) that was matched to the IEEE693 spectrum at 2% and 5% of the critical damping with the subsequent final match to a 2% damped spectrum. In contrast, the seed motions in this study were matched to a 5% damped spectrum only. As a result, an excellent spectral matching with about ±7% tolerance was achieved for the wide frequency range from 0.13 Hz to 33.3 Hz for all non-stationary time histories.

Each seed motion was matched to the target IEEE693 spectrum by using both wavelet options, the so-called Model 6 and Model 7 (Al Atik et al, 2010). The use of the tapered cosine wave as an adjustment function in Model 6 has the advantage of preserving the non-stationary character of the acceleration time histories. However, this adjustment function introduces drift to the velocity and displacement time histories. As a result, it requires applying an additional baseline correction to the adjusted acceleration. Model 7 utilizes a wavelet with a modified taper, the Gaussian taper, so the adjustment wavelet is smooth and continuous. As a result, the wavelet ends with zero velocity and displacement and no drift appears in the velocity and displacement time histories of the adjusted ground motion. The matched time histories were checked to ensure that the bracketed duration and the strong part ratio meet and exceed the threshold values established by the IEEE Std 693-2005 and IEEE P693/D16.

2.2 IEEE693-SPECTRUM-COMPATIBLE SYNTHETIC TIME HISTORIES

Three three-component synthetic strong motion time histories compatible with IEEE693 requirements were generated in order to have an option of using time histories generated from a set of harmonics. SimQke-1 (Vanmarcke, 1976; Gasparini, 1976) was used in the generation of these synthetic strong motion time histories. SimQke-1 is a FORTRAN-based program that generates a synthetic time history, the spectrum of which matches the target spectrum.

The matching was performed at a 5% damping. Since the tolerance between the target spectrum and the acceleration spectra had quite large variations, a total of 399 single-component synthetic strong motion time histories were generated. Nine single-component time histories (three three-component time histories) with the best match to the target spectrum were selected. The main criterion for adequate matching was to limit the variations from the target spectrum to about ±7% in the wide range of frequencies from 0.13 Hz to 33.3 Hz at 1/24th octave resolution. In many cases the spectra of time histories generated by SimQke significantly exceeded this tight tolerance threshold. To address this issue, all synthetic time histories were subsequently matched to the same target response spectrum. The latter matching was performed in a time domain by utilizing RspMatch09. One of the typical results of this approach is presented in Figure 2-1.

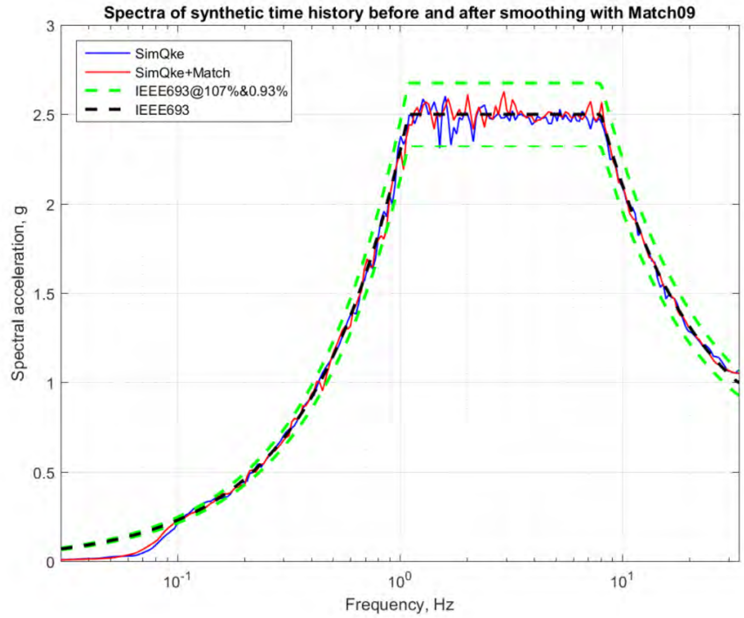


Figure 2-1. Spectra of synthetic time history (SQ-009.acc) before and after subsequent matching in a time domain by RspMatch09

2.3 RESULTANT IEEE693-SPECTRUM-COMPATIBLE TIME HISTORIES

The following naming convention was adopted. The name of the IEEE693-spectrum-compatible time history starts from "TestQke4IEEE5", where 5 stands for the 5% damping. The name ends with a number preceded by a dash. This is a sequential number of the time history. This study developed eight three-component time histories. The first five were generated from the seed motions and the last three are the synthetic strong motions as presented in Table 2-1. The seed motions were obtained from the PEER NGA-West2 (Ancheta et al, 2003) and the CESMD (CESMD, 2016) databases.

Table 2-1. List of IEEE693-spectrum-compatible time histories developed in the study

Seed motion, if any	EQ type	Name of IEEE693-spectrum-compatible time history
El-Centro, CA (1940)	Crustal	TestQke4IEEE5-1
Landers, CA (1992)	Crustal	TestQke4IEEE5-2
Chi-Chi, Taiwan (1999)	Crustal	TestQke4IEEE5-3
El Mayor-Cucapah, Mexico (2010)	Crustal	TestQke4IEEE5-4
CONSTITUCIONS/N4598 Chile, February 27, 2010	Subduction	TestQke4IEEE5-5
NA (synthetic)	NA	TestQke4IEEE5-6
NA (synthetic)	NA	TestQke4IEEE5-7
NA (synthetic)	NA	TestQke4IEEE5-8

Note that TestQke4IEEE5-5 is developed from a subduction earthquake seed motion. Subduction earthquakes are not addressed by IEEE P693/D16. Although this record was developed to satisfy the requirements specified in IEEE P693/D16, its main purpose was as an aid to research on investigating equipment response to subduction events.

The resultant time histories are presented in Figure 2-2 – Figure 2-17. The plots are organized as follows. The first group of plots shows the acceleration time history and spectral plot for each component. For example, the acceleration time history and the spectral accelerations for the TestQke4IEEE5-1. The second group of plots shows the change of the Power Spectral Density (PSD) in time compared to the acceleration time history. These plots show the variation of the frequency content of each component in time. For example, Figure 2-3 shows the acceleration time histories and the PSD variations in time for each component of the TestQke4IEEE5-1.

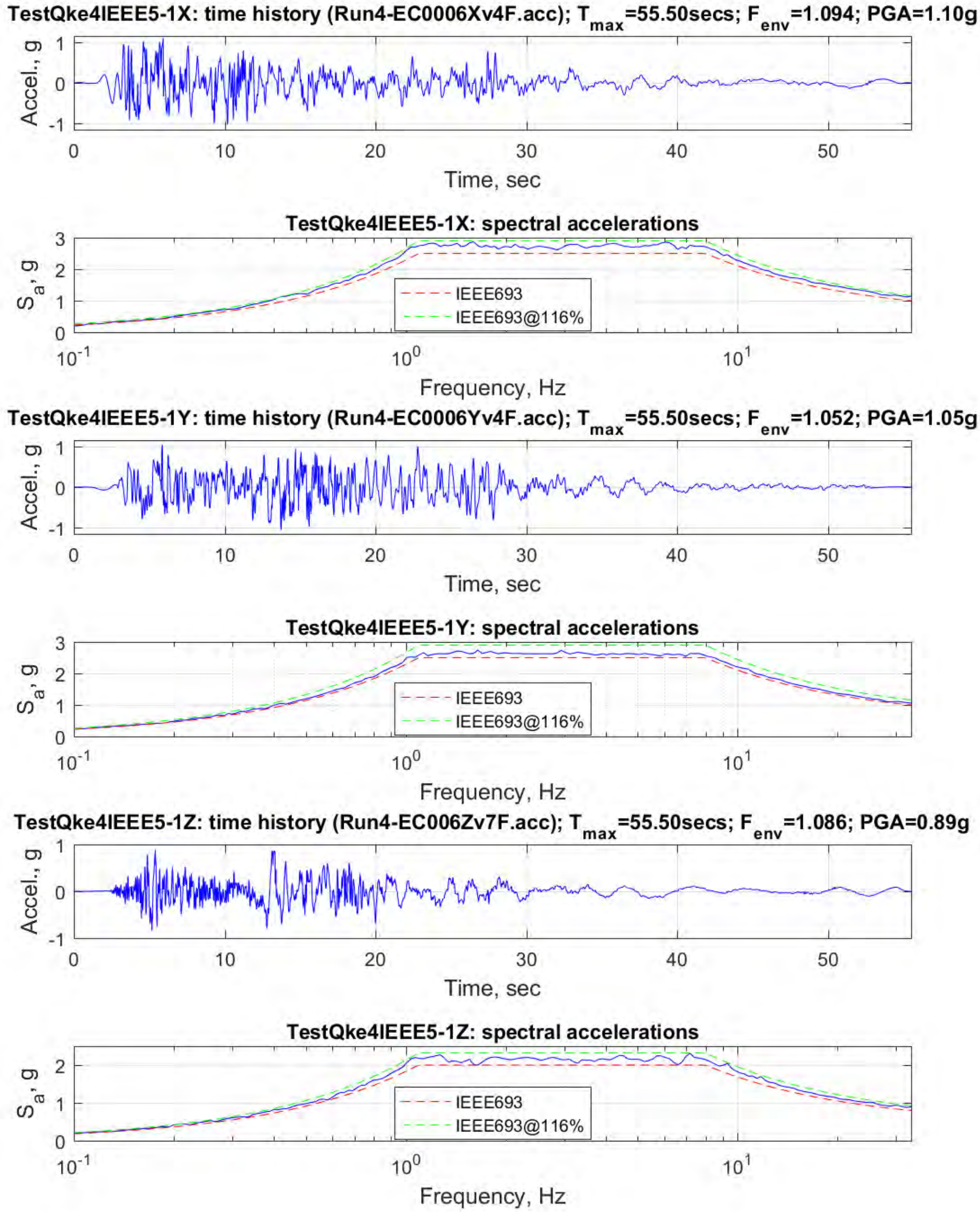


Figure 2-2. IEEE693-spectrum-compatible time history matched to IEEE693 spectrum at 5% damping (TestQke4IEEE5-1 matched from 1940 El-Centro seed record)

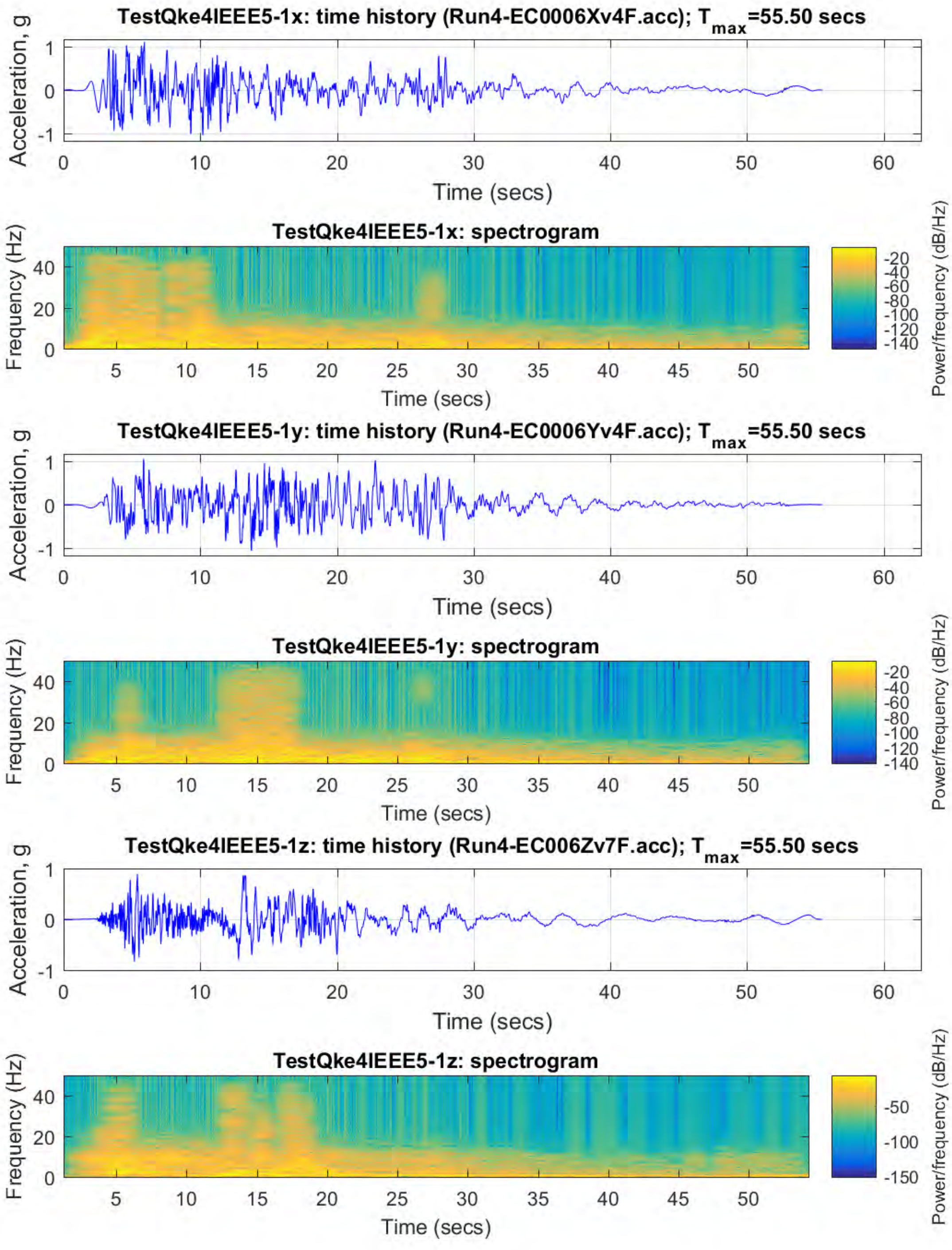


Figure 2-3. Variation of the Power Spectral Density in time (TestQke4IEEE5-1)

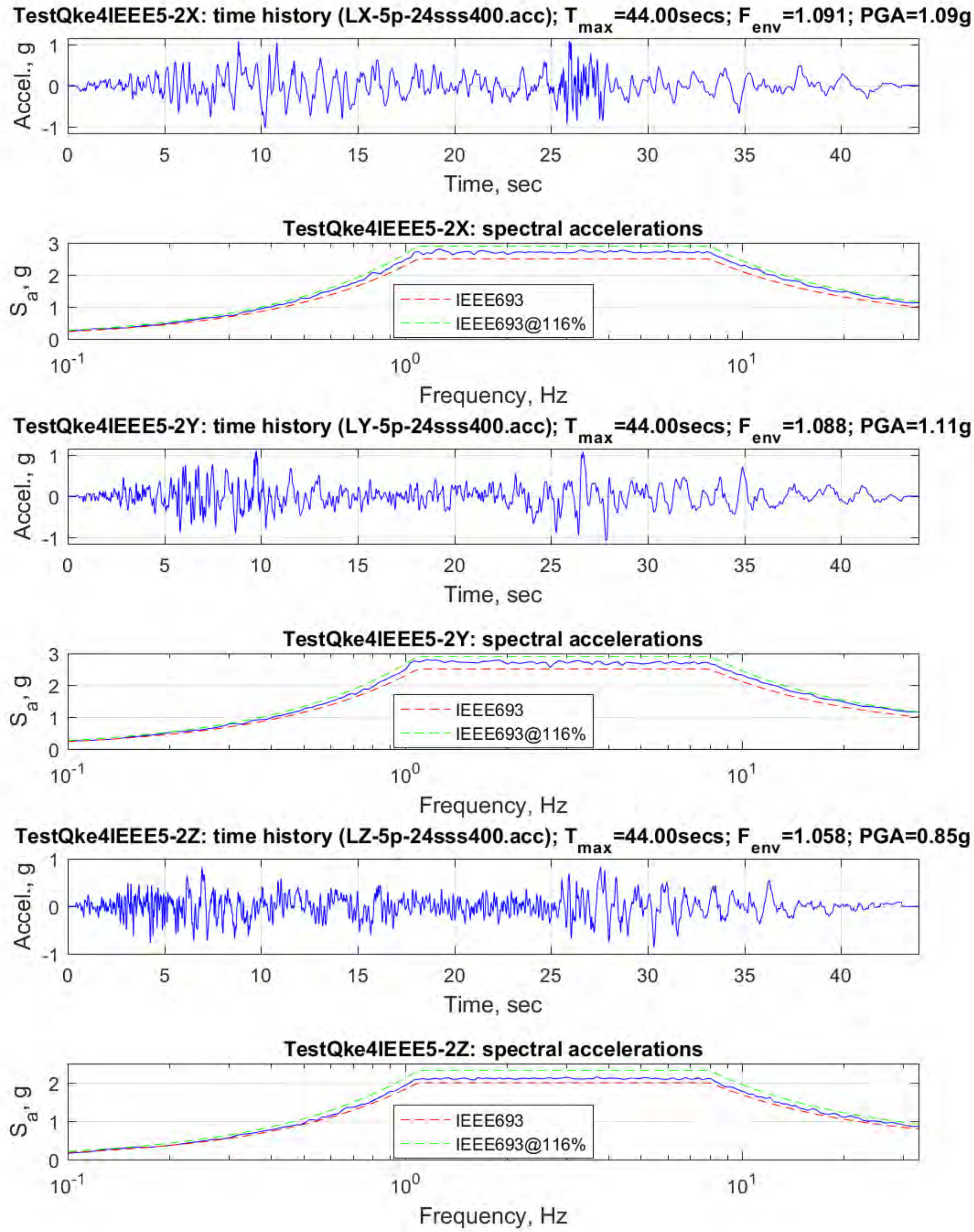


Figure 2-4. IEEE693-spectrum-compatible time history matched to IEEE693 spectrum at 5% damping (TestQke4IEEE5-2 matched from 1992 Landers seed record)

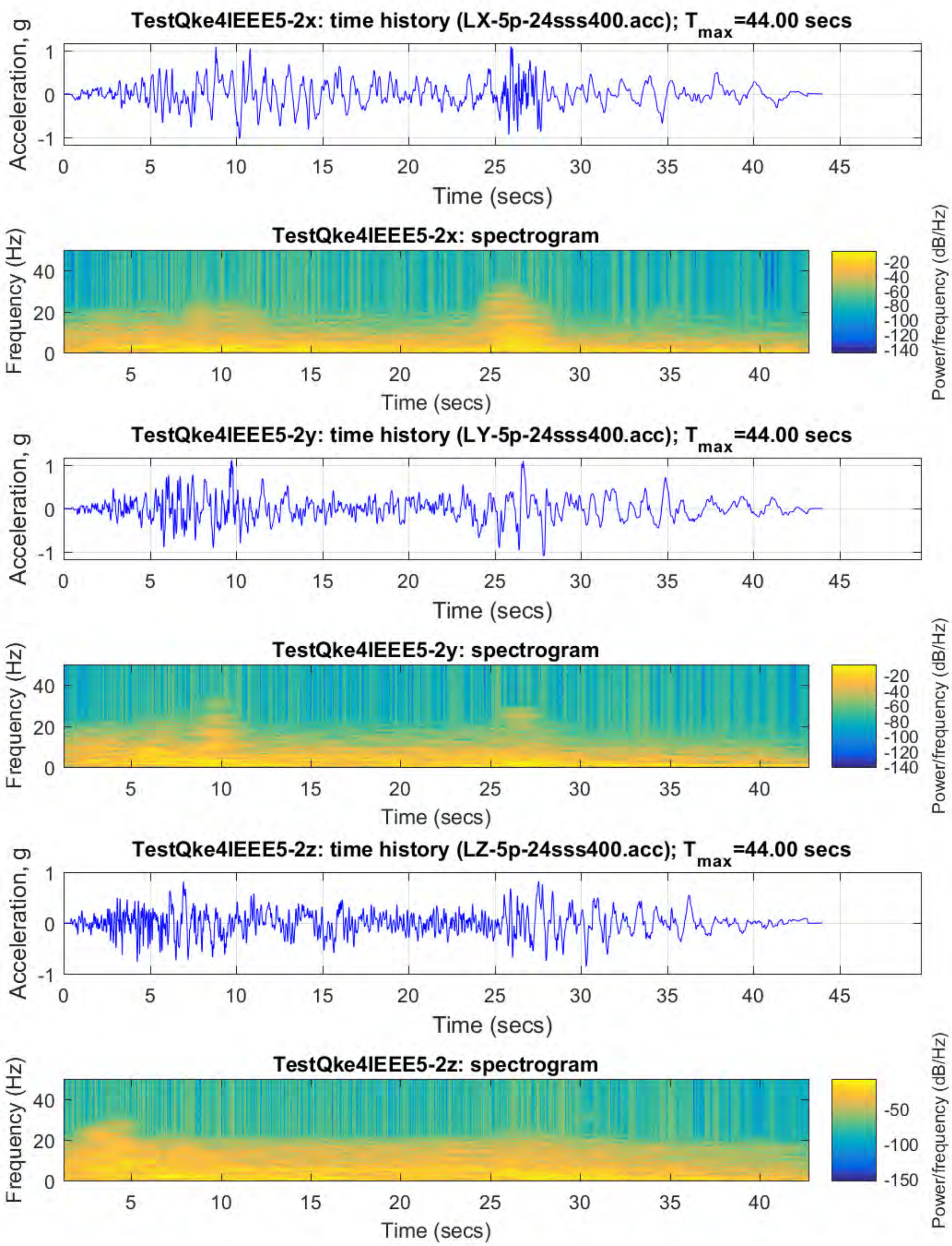


Figure 2-5. Variation of the Power Spectral Density in time (TestQke4IEEE5-2)

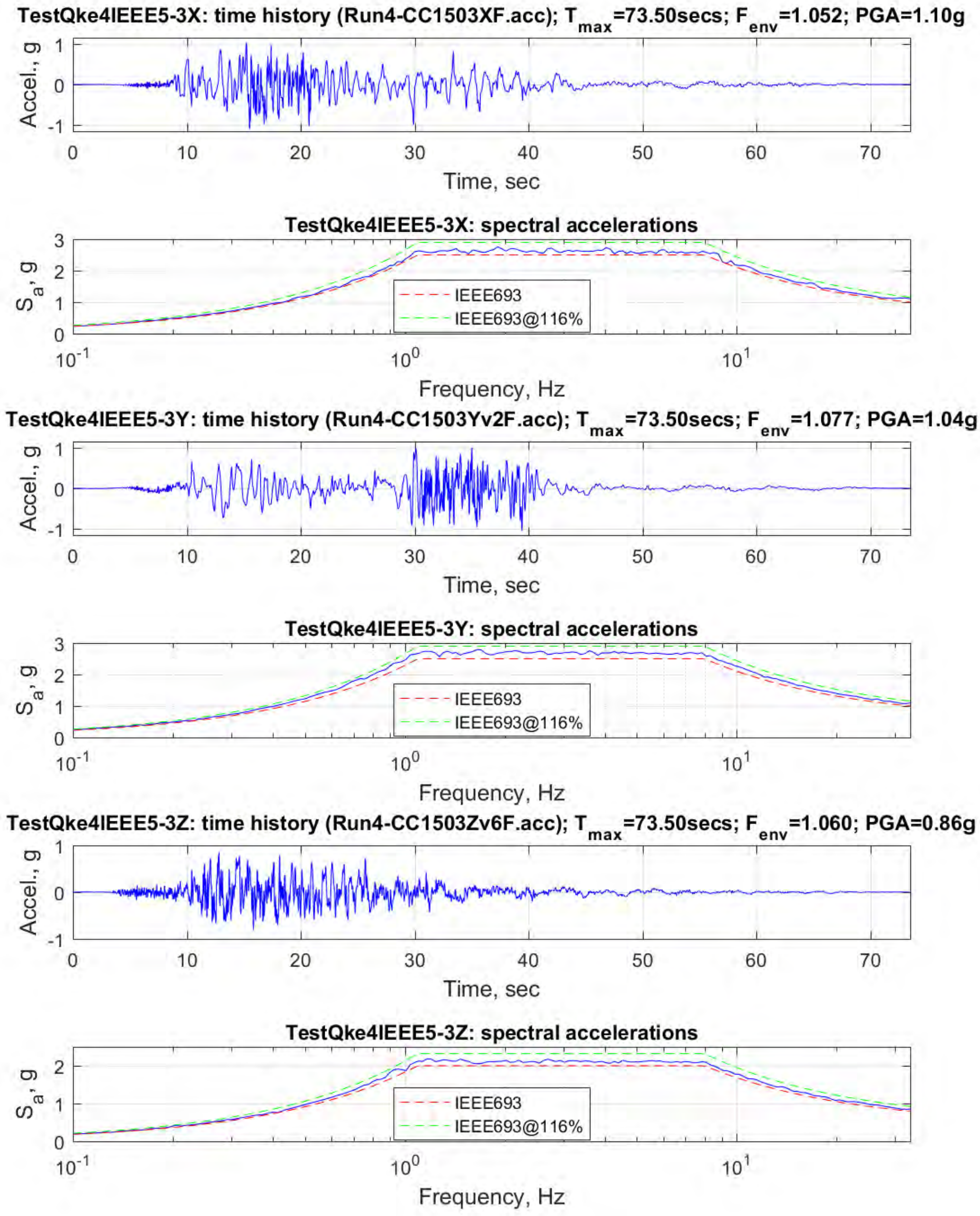


Figure 2-6. IEEE693-spectrum-compatible time history matched to IEEE693 spectrum at 5% damping (TestQke4IEEE5-3 matched from 1999 Chi-Chi seed record)

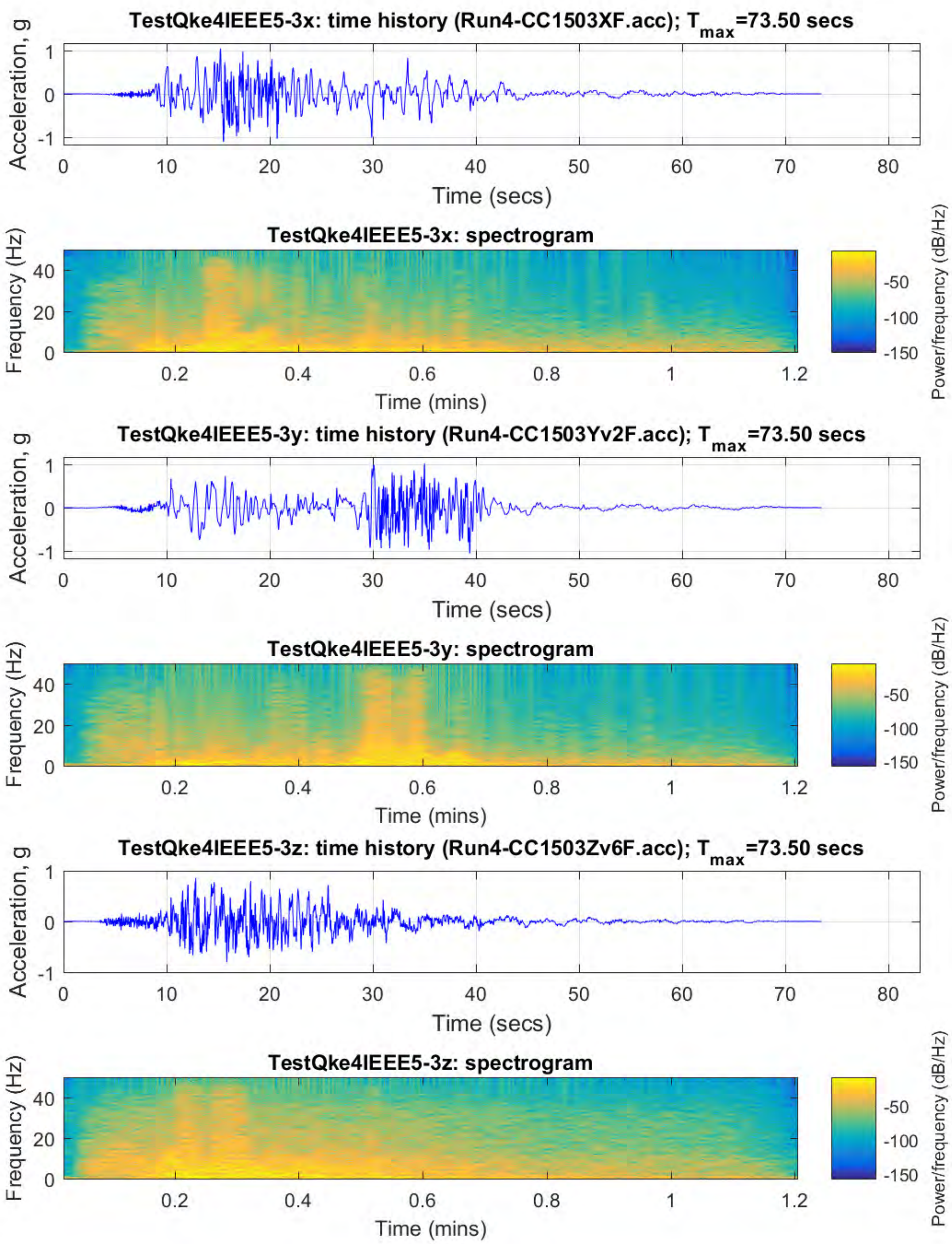


Figure 2-7. Variation of the Power Spectral Density in time (TestQke4IEEE5-3)

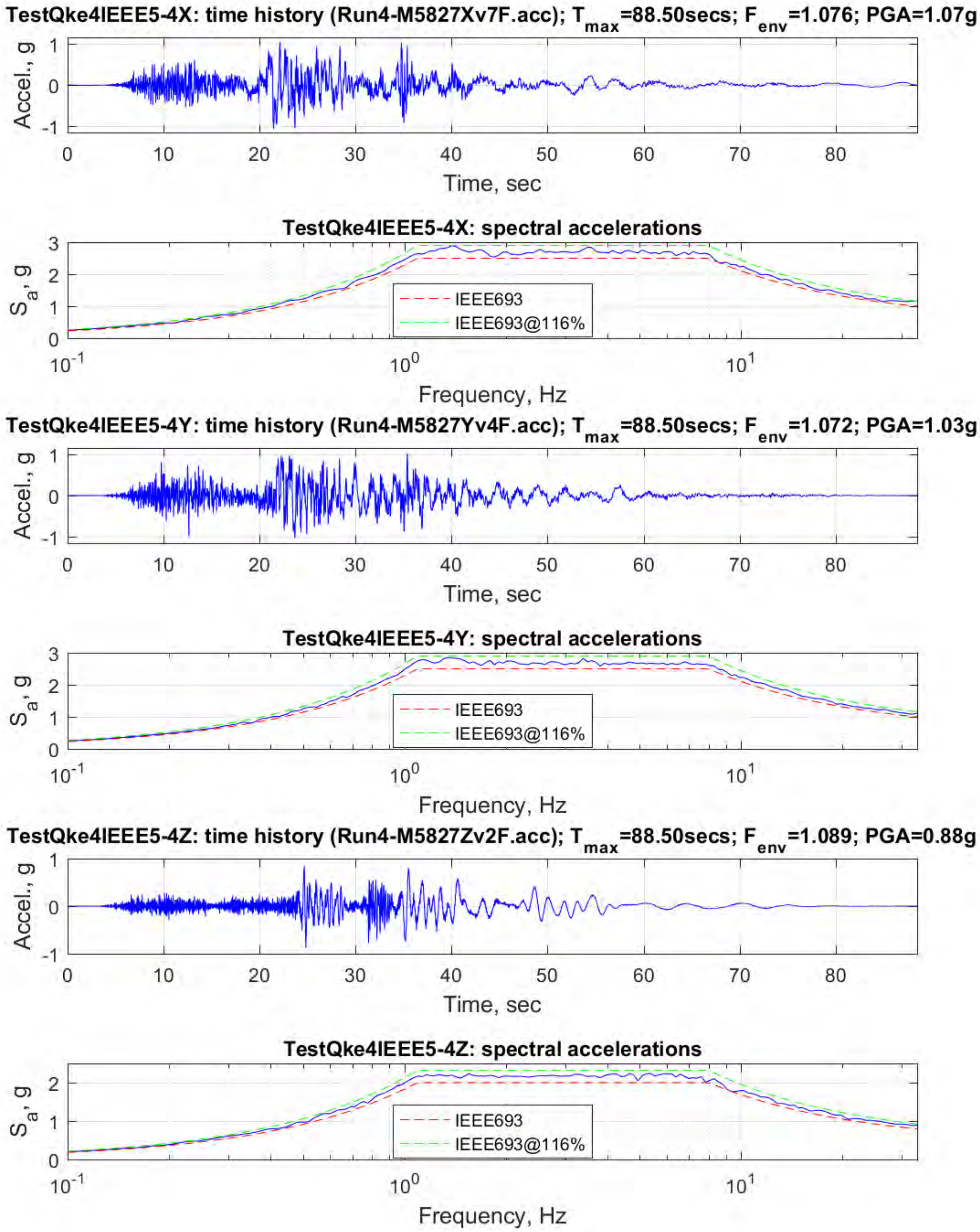


Figure 2-8. IEEE693-spectrum-compatible time history matched to IEEE693 spectrum at 5% damping (TestQke4IEEE5-4 matched from 2010 El Mayor-Cucapah seed record)

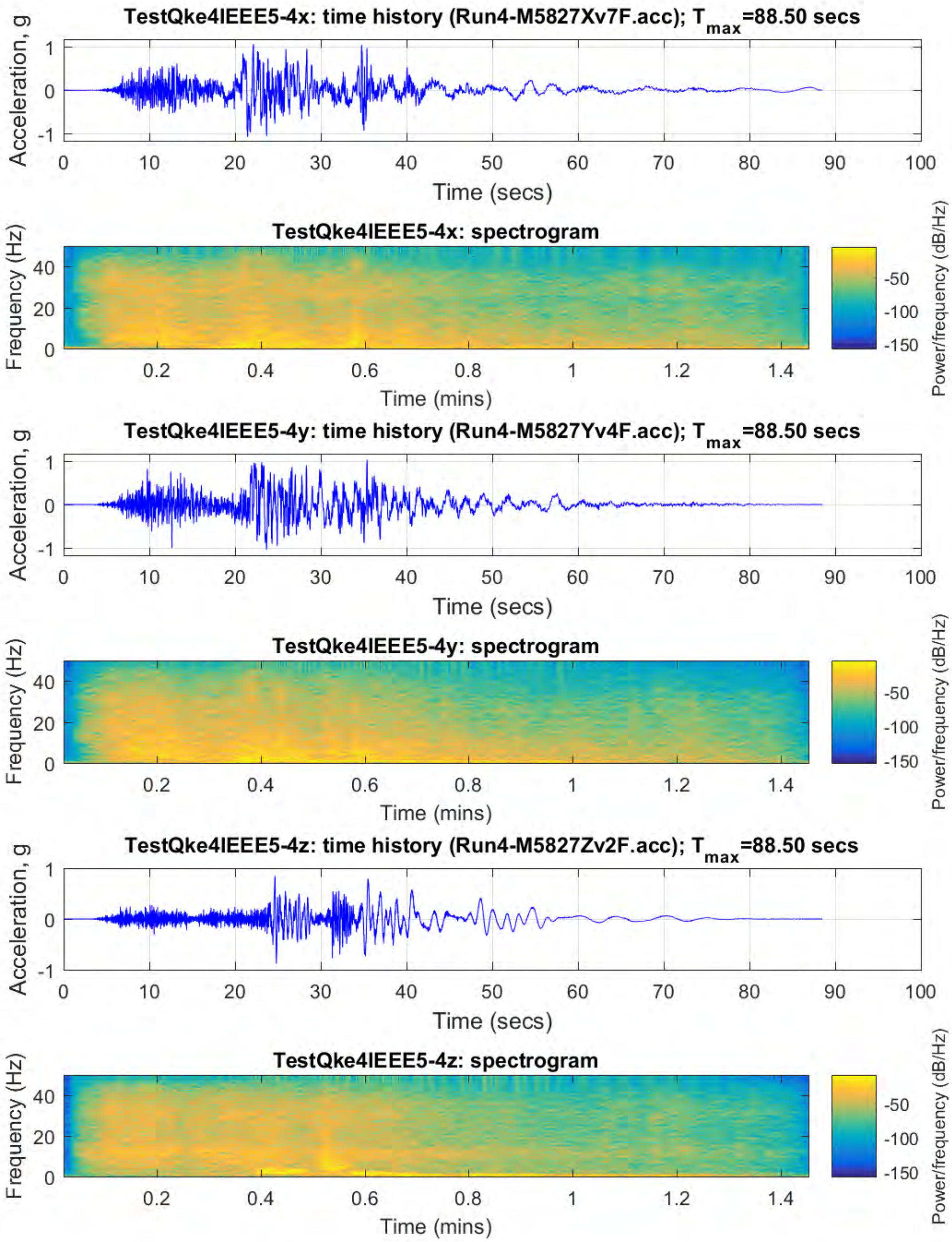


Figure 2-9. Variation of the Power Spectral Density in time (TestQke4IEEE5-4)

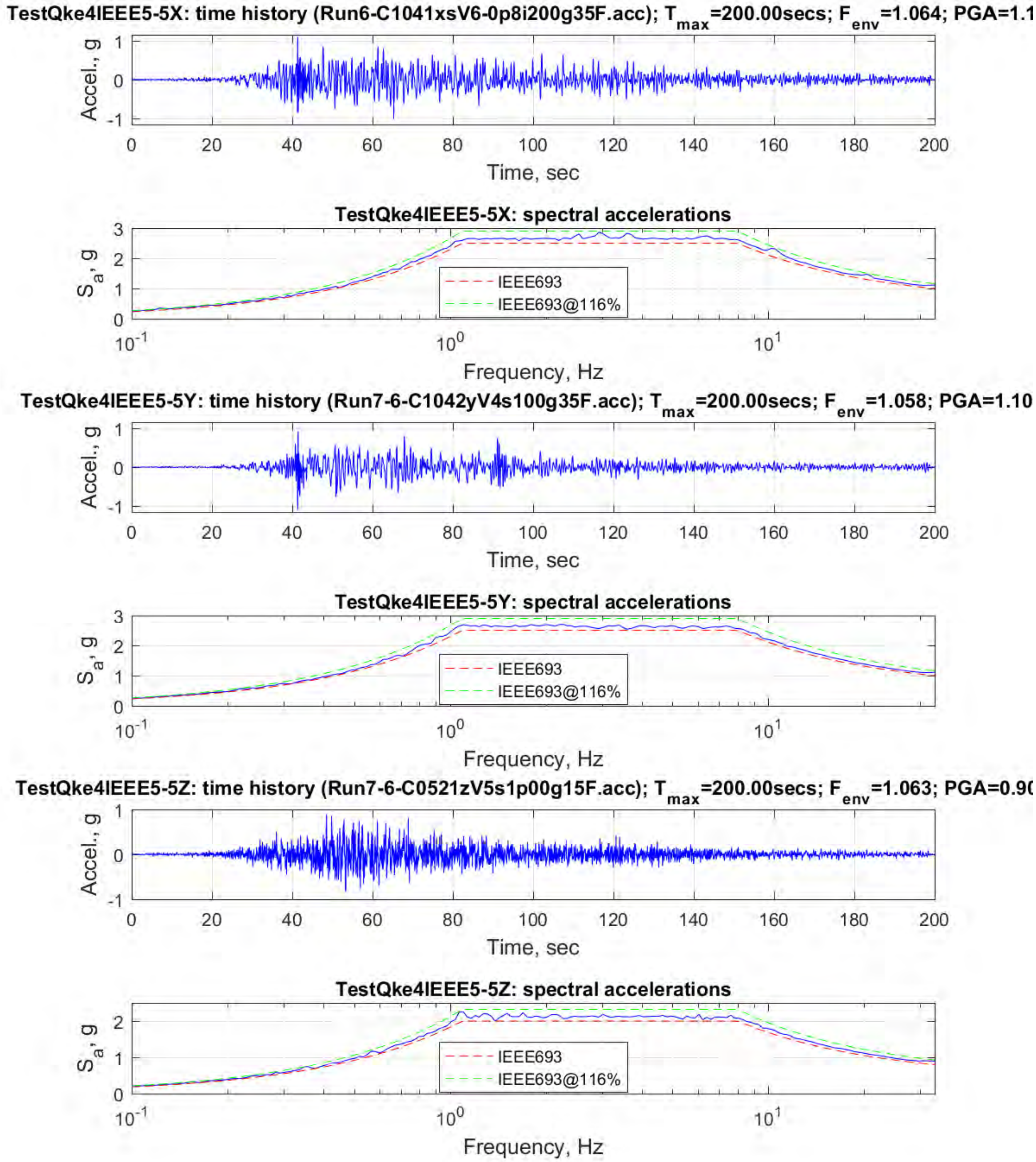


Figure 2-10. IEEE693-spectrum-compatible time history matched to IEEE693 spectrum at 5% damping (TestQke4IEEE5-5 matched from subduction seed record)

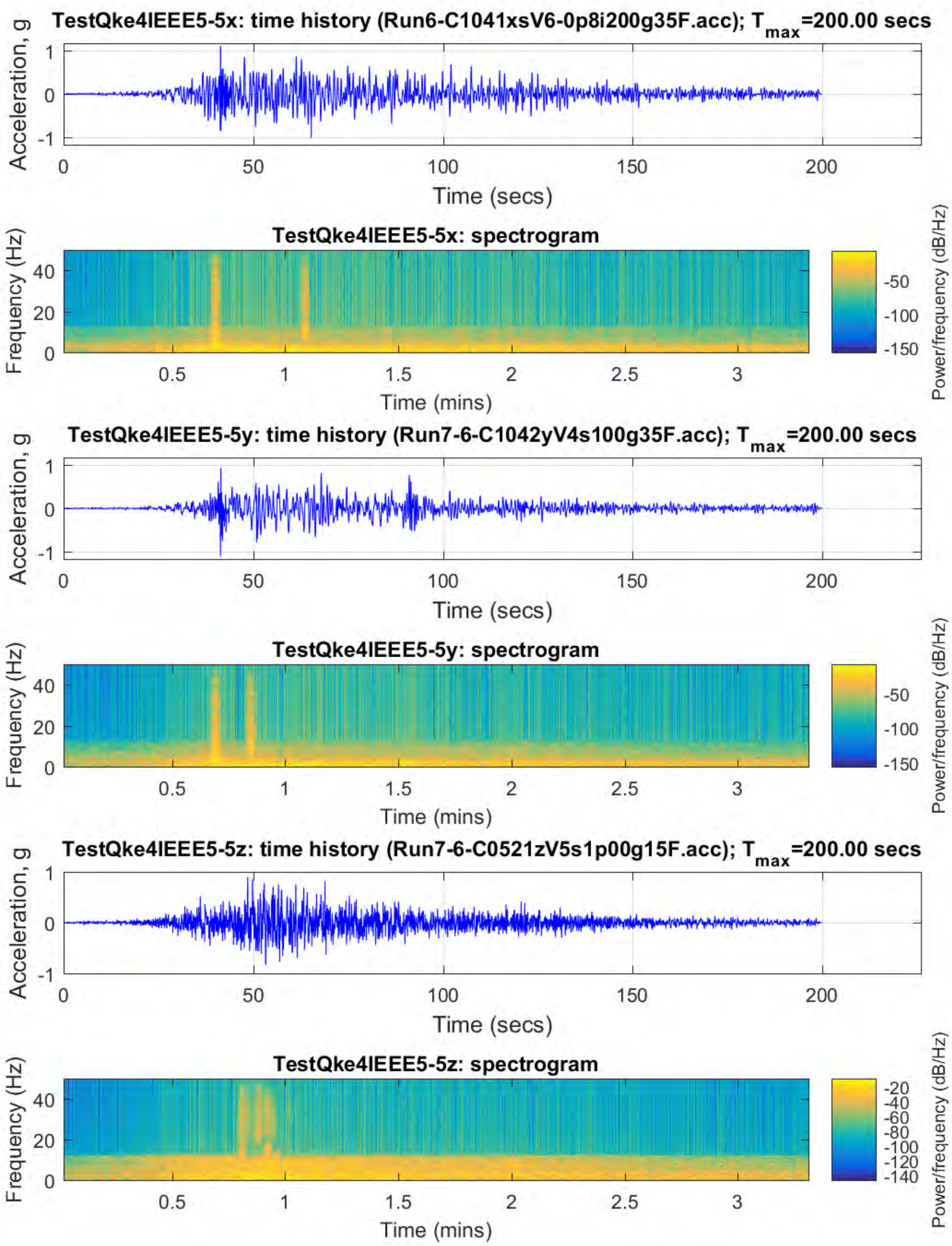


Figure 2-11. Variation of the Power Spectral Density in time (TestQke4IEEE5-5)

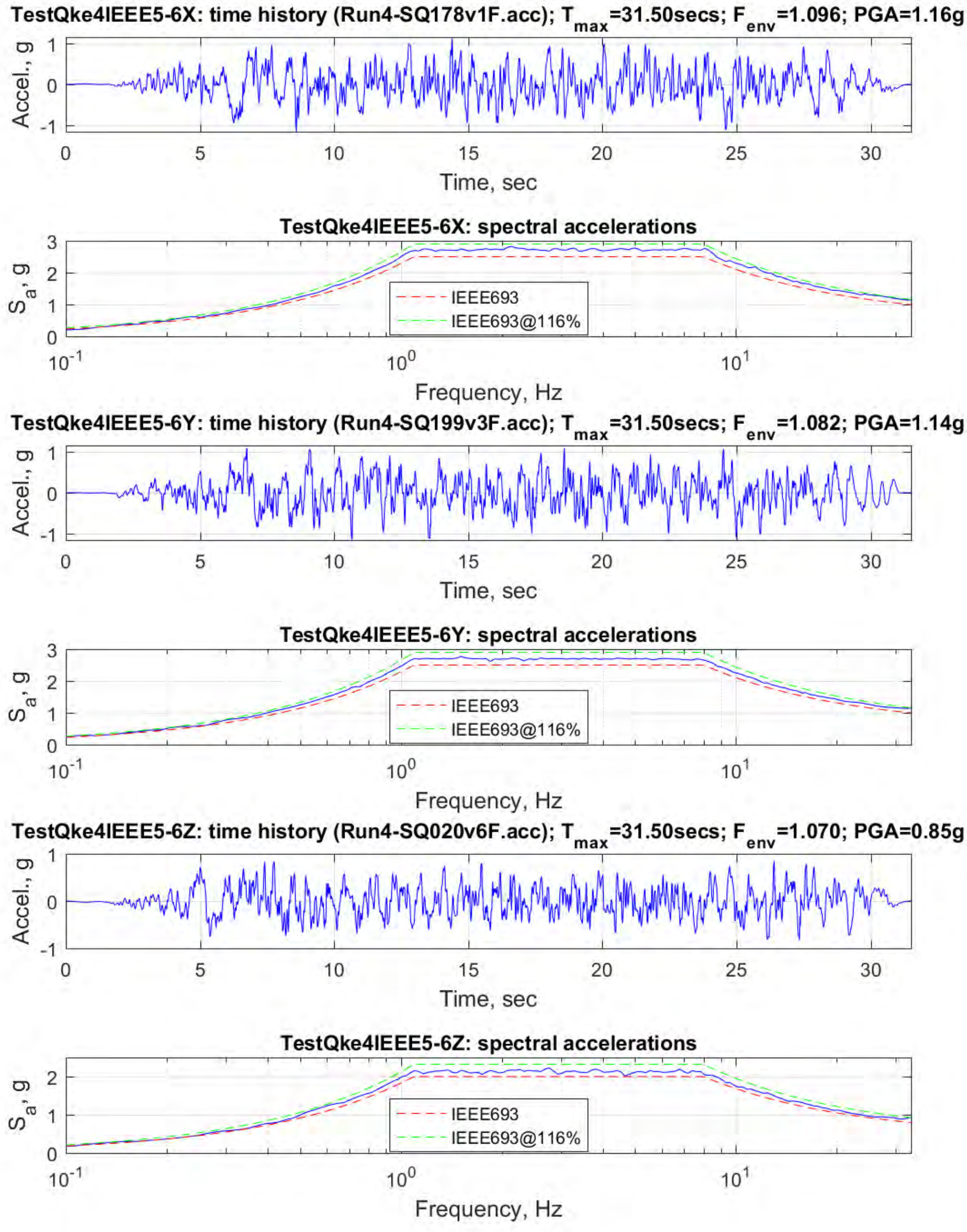


Figure 2-12. IEEE693-spectrum-compatible time history matched to IEEE693 spectrum at 5% damping (TestQke4IEEE5-6, synthetic)

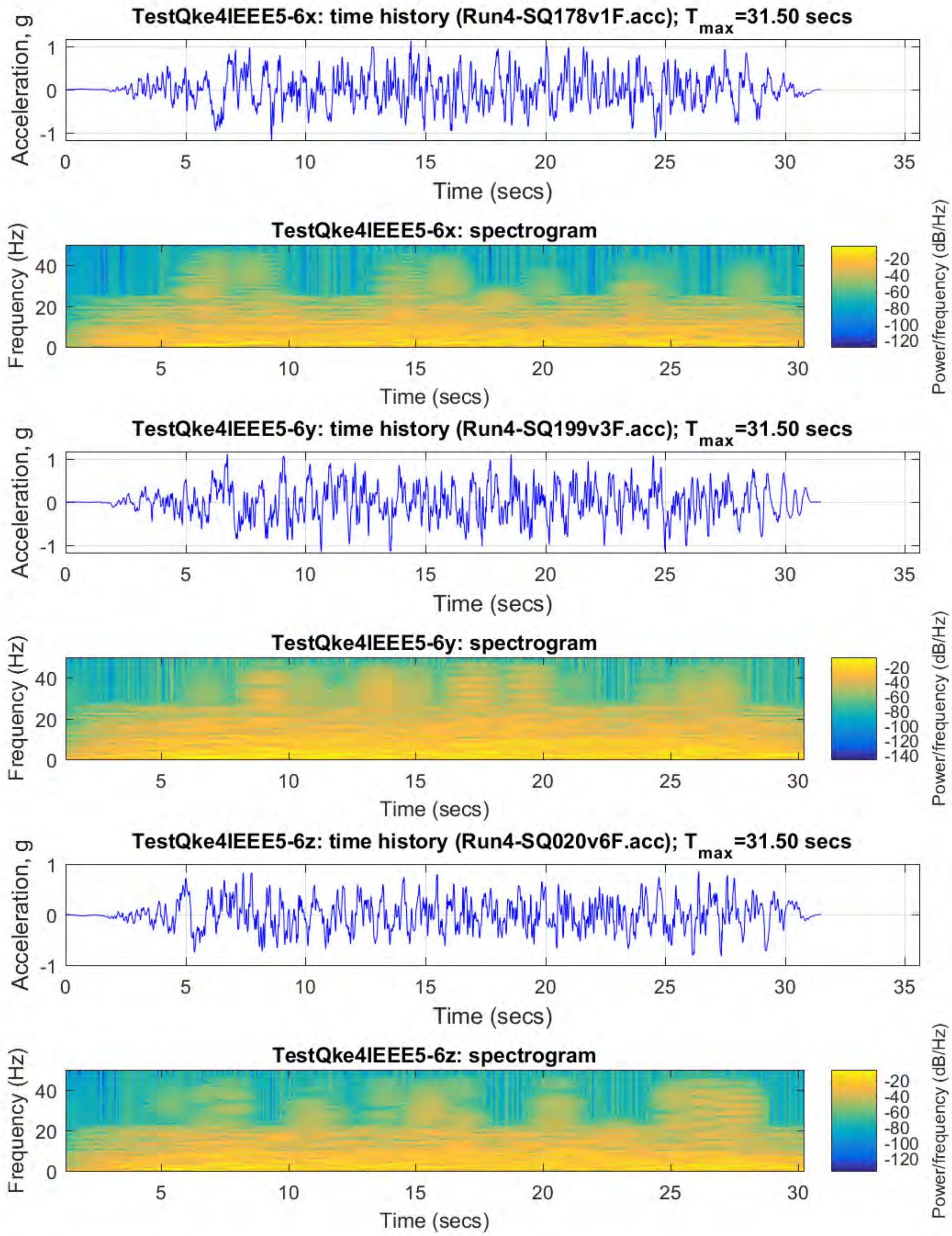


Figure 2-13. Variation of the Power Spectral Density in time (TestQke4IEEE5-6)

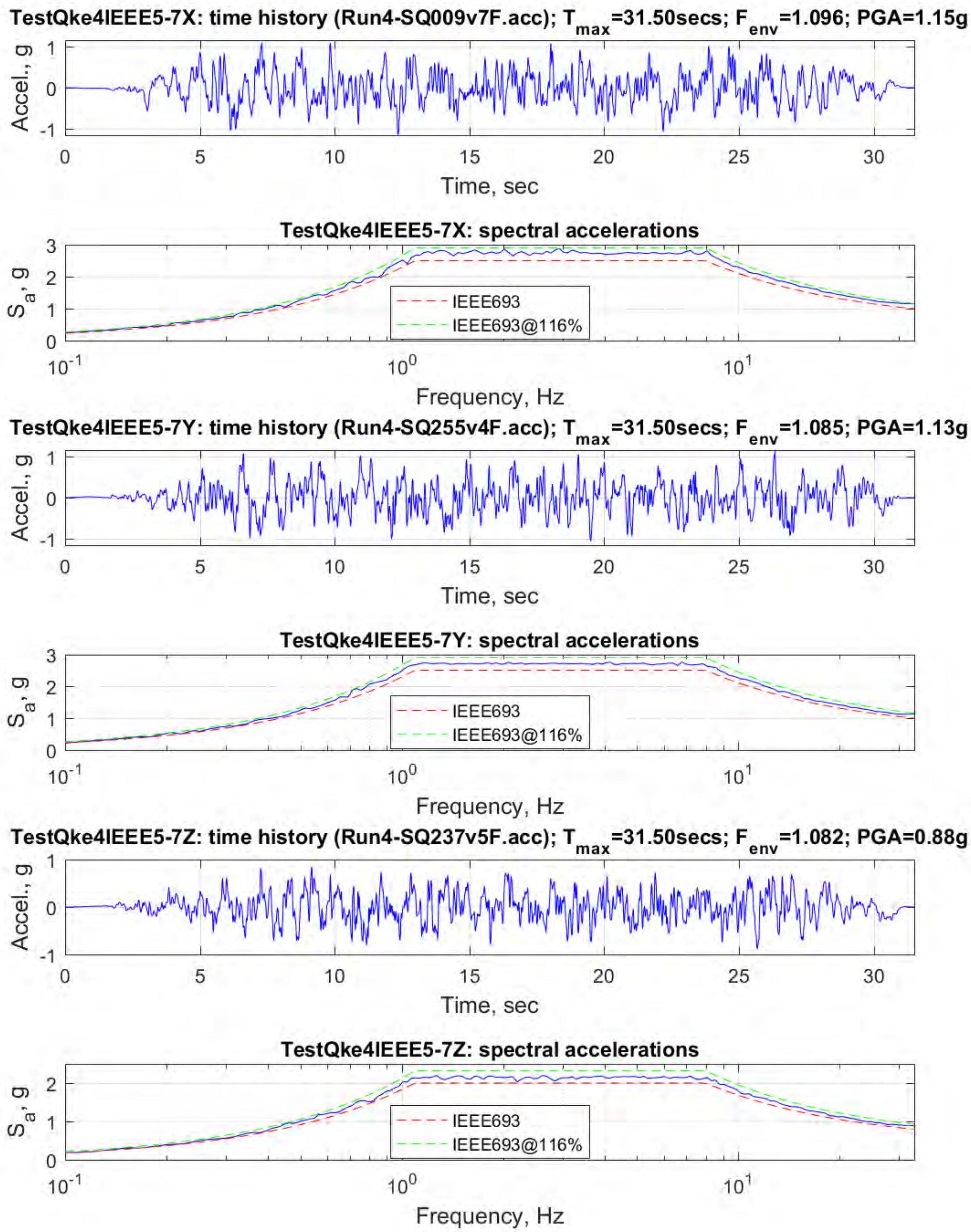


Figure 2-14. IEEE693-spectrum-compatible time history matched to IEEE693 spectrum at 5% damping (TestQke4IEEE5-7, synthetic)

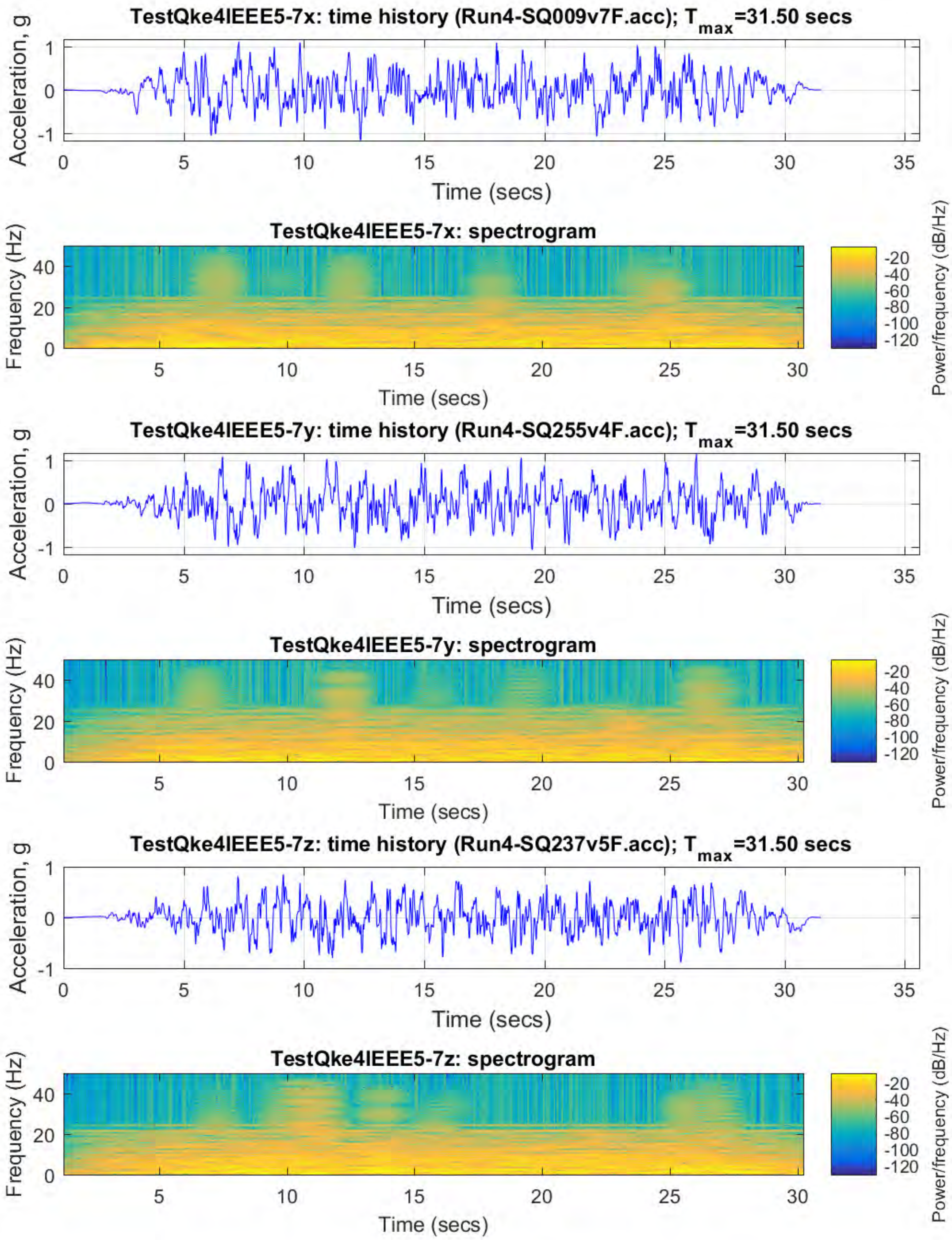


Figure 2-15. Variation of the Power Spectral Density in time (TestQke4IEEE5-7)

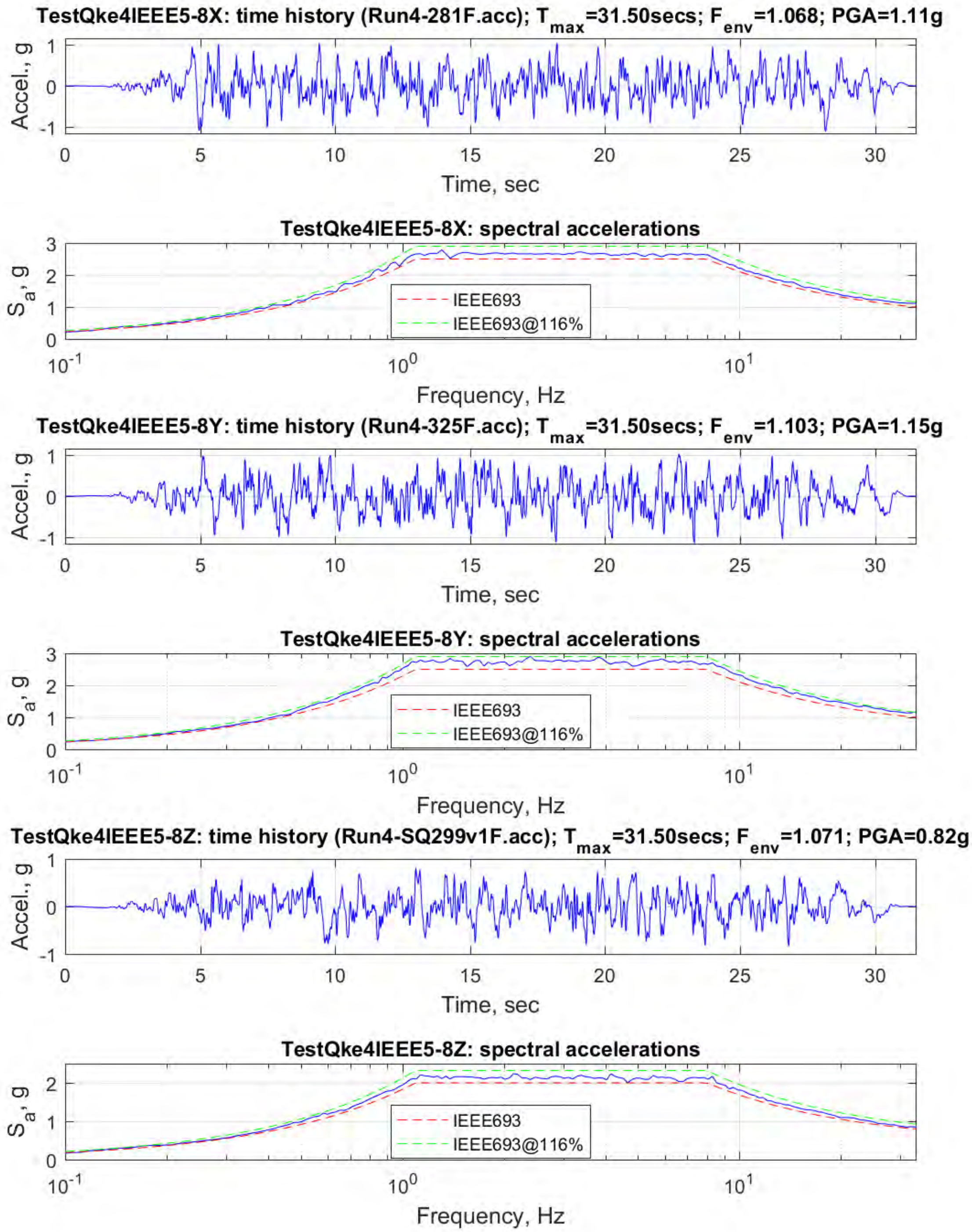


Figure 2-16. IEEE693-spectrum-compatible time history matched to IEEE693 spectrum at 5% damping (TestQke4IEEE5-8, synthetic)

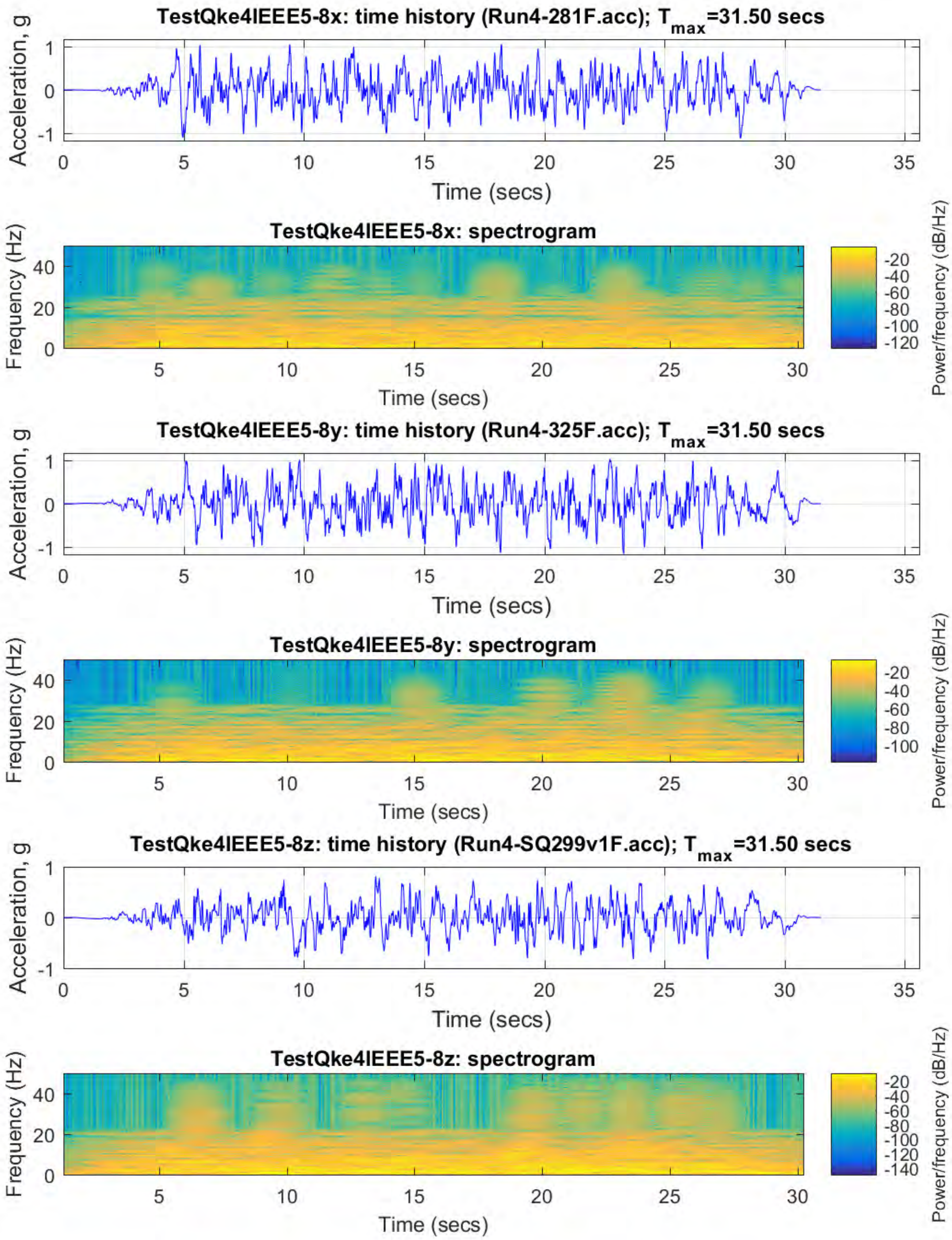
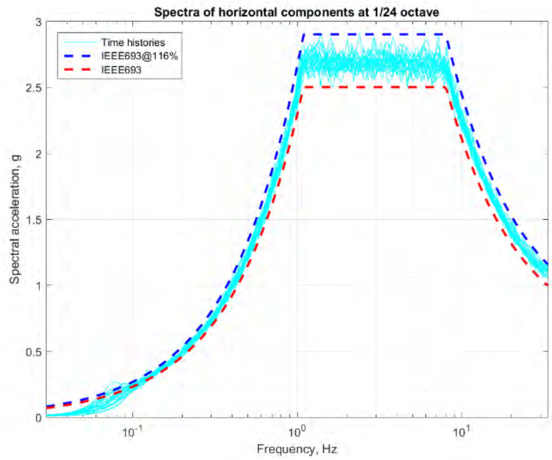
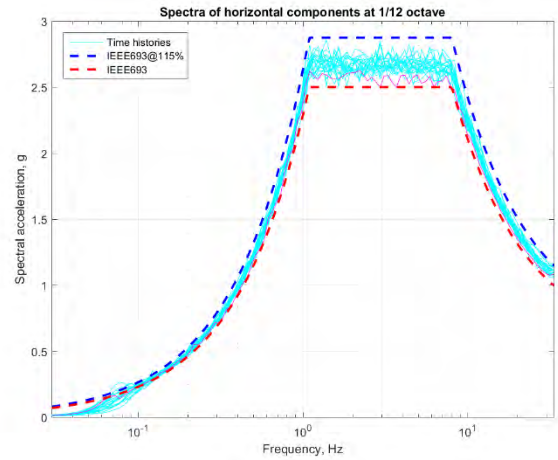


Figure 2-17. Variation of the Power Spectral Density in time (TestQke4IEEE5-8)

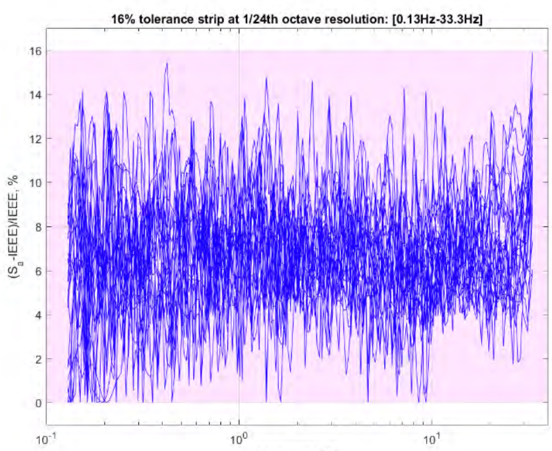
All resultant time histories have spectra closely enveloping the IEEE693 from 0.13 Hz to 33.3 Hz as presented in Figure 2-18. At 1/24th octave resolution all spectral accelerations meet and exceed the IEEE693 spectrum and they stay within 16% of the target spectrum. In the case of the 1/12th octave frequency resolution, this tolerance above the target response spectrum is limited by 15%.



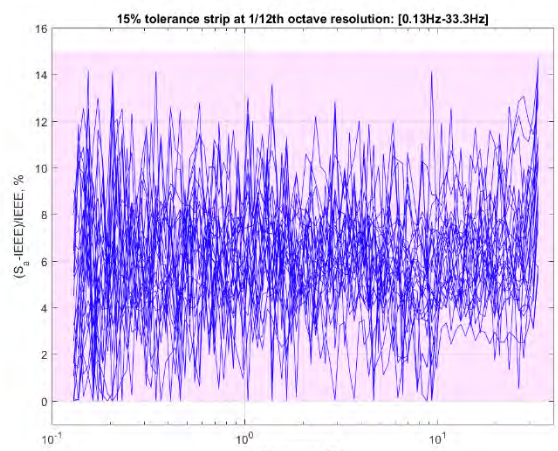
a) All spectra fit into a 16% strip above the IEEE693 High PL at 1/24th octave resolution



b) All spectra fit into a 15% strip above the IEEE693 High PL at 1/12th octave resolution



c) (S_a-IEEE)/IEEE ratio at 1/24th octave



d) (S_a-IEEE)/IEEE ratio at 1/12th octave

Figure 2-18. The resultant time histories have spectra closely enveloping the IEEE693 from 0.13 Hz to 33.3 Hz

The strong part ratio and bracketed duration (IEEE, 2005) of all IEEE compatible records exceed the minimum requirements of the IEEE Std 693-2005 (IEEE, 2005) and IEEE P693/D16 (IEEE 693 WG, 2017) as presented in the two top plots of Figure 2-19. The total cumulative energy is presented in the third plot from the top. The cycle count does not fall below one cycle as shown in the fourth plot from the top. The factor at best fit, K_S (Takhirov et al, 2017a and Takhirov et al, 2017c), is very close to unity as presented in the fifth plot from the top. Because of the close match to the IEEE693 spectrum, the cumulative distance, D_{SA} (Takhirov et al, 2017a and Takhirov et al, 2017c), from the target spectra at best fit is very small and does not exceed 0.7 as shown in the bottom plot.

The number of high cycles in the SDOF response is presented in Figure 2-20. The magenta dashed line is a threshold specified in IEEE693 (IEEE, 2005). Since the number of high cycles in the SDOF response is expected to be less for systems with higher damping, the number of cycles for the 5% damped systems is less than the threshold of the two cycles established by the IEEE Std 693-2005 (IEEE, 2005) for the 2% damped systems. This was observed earlier in the study of the historic records. Based on the results of this study and the change to spectrum matching at 5% damping, the high cycle count provision has been removed from the requirements given in IEEE P693/D16 (IEEE693 WG, 2017).

The acceleration, velocity and displacement plots are presented in Appendix A. The spectral plot for each component of the time history is presented at the bottom of each figure. It also shows the frequency from which enveloping of the IEEE693 spectrum begins.

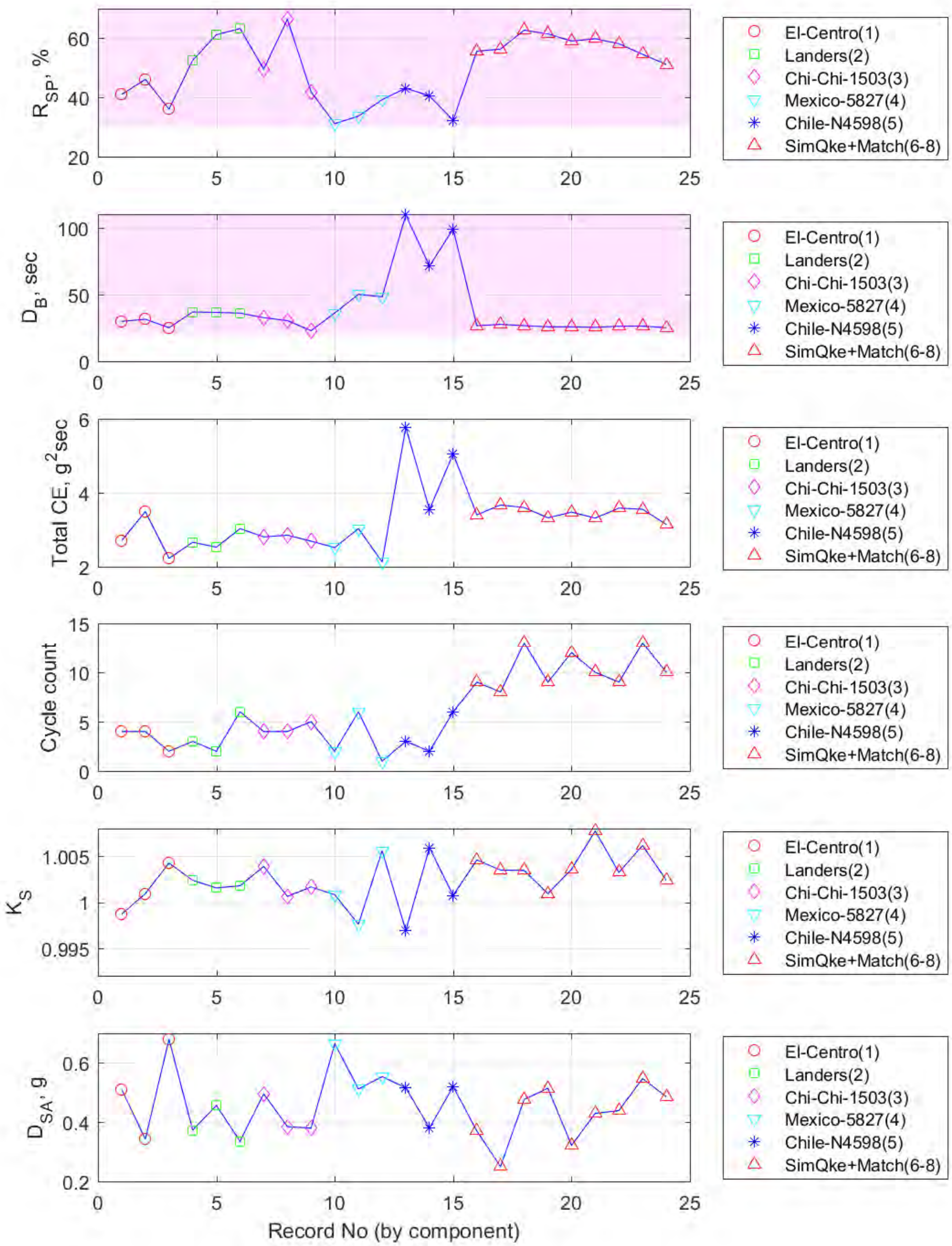


Figure 2-19. Major parameters of the IEEE693-spectrum-compatible time histories

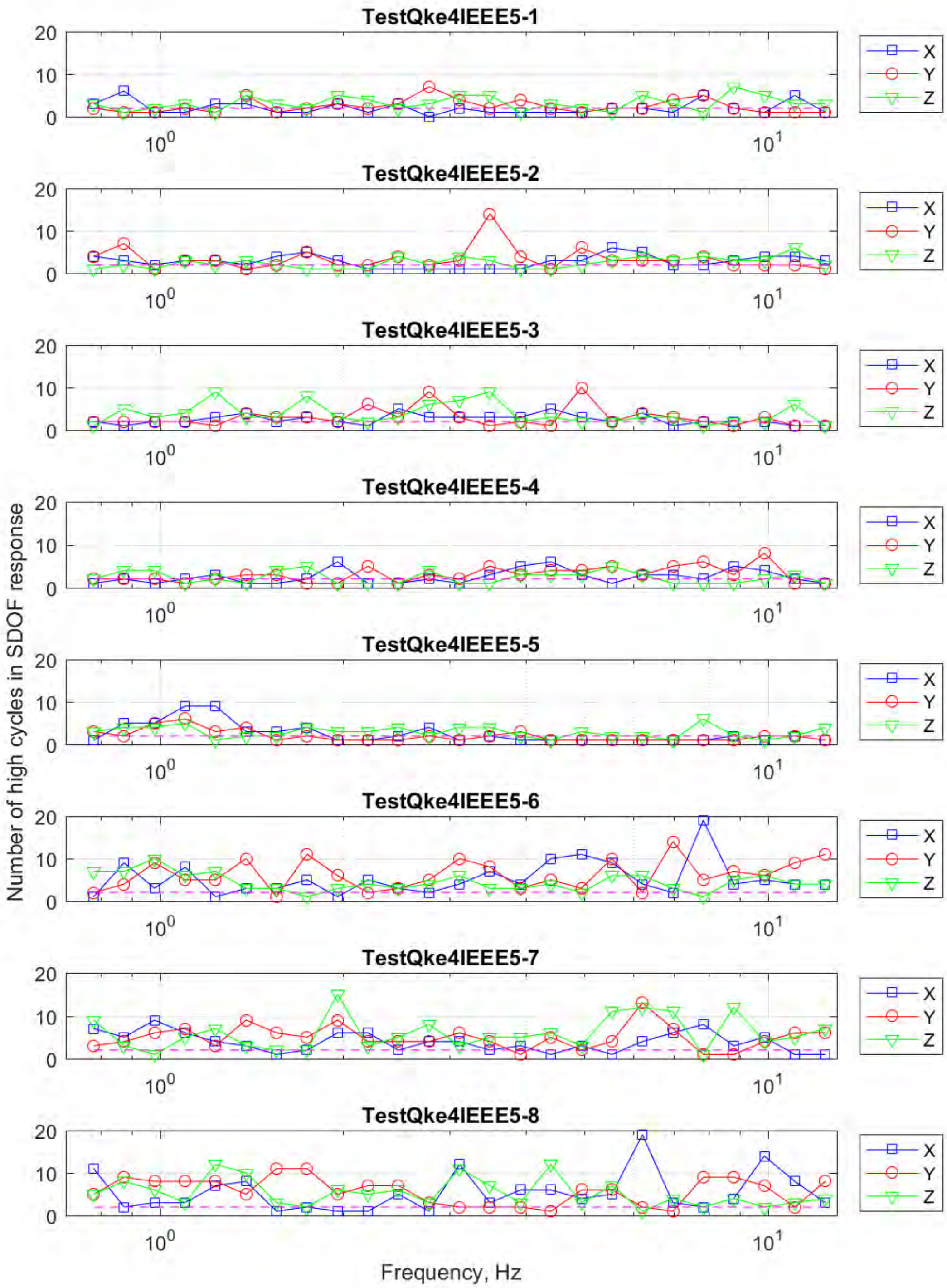


Figure 2-20. Number of cycles in the 5%-damped SDOF response (magenta is a threshold specified in IEEE Std 693-2005 (IEEE, 2005)

3 Filtered Versions of TestQke4IEEE5

Since enveloping of the IEEE693 spectrum starts from 0.13 Hz all time histories developed in this study impose large displacement demand. While this is acceptable for analysis, the time histories need to be filtered to meet the limitations of the existing shaking tables. The limitations of the major shaking tables worldwide is presented in Table 3-1. It is selected from the world list of shaking tables (Wikipedia, 2017) by limiting the selection to 3D and 6D shaking tables and to uniaxial shaking tables with long stroke.

Table 3-1. A world list of 3D and 6D shaking tables and 1D shaking tables with long stroke

No	Region	Country	State	Name, location	Size, m	MT	DOF	D_X, mm	D_y, mm	D_z, mm	V_X, mm/s	V_y, mm/s	V_z, mm/s
1	Africa	Algeria	-	CGS Laboratory, Alger	6.1 x 6.1	60	6	±150	±250	±100	±1100	±1100	±1000
2	Africa	South Africa	-	University of Witwatersrand, Johannesburg	4 x 4	10	1	±750	n/a	n/a	±1000	n/a	n/a
3	Asia	China	-	China Academy of Building Research, Beijing	6.1 x 6.1	60	6	±150	±250	±100	±1000	±1200	±800
4	Asia	China	-	Guangzhou University	3 x 3	20	6	±100	±100	±50	±1000	±1000	±1000
5	Asia	China	-	Nanjing University of Technology	3 x 5	15	3	±120	±120	±120	±500	±500	±500
6	Asia	China	-	Tongji University, Shanghai	4 x 4	25	6	±100	±50	±50	±1000	±600	±600
7	Asia	India	Karnataka	IISc, Bangalore	1 x 1	0.5	6	±220	±220	±100	±570	±570	±570
8	Asia	India	Tamil Nadu	Indira Gandhi Centre for Atomic Research(IGCAR), Chennai,Tamil Nadu	3 x 3	10	6	±100	±100	±100	300	300	?
9	Asia	Japan	-	NIED 'E-Defence' Laboratory, Miki City	20 x 15	1200	6	±1000	±1000	±500	±2000	±2000	±700
10	Asia	Japan	-	Hazama Corp Ltd.	6 x 4	80	3	±300	±150	±100	±1150	?	?
11	Asia	Japan	-	Ishikawajima Harima Heavy Ind Corp.	4.5 x 4.5	35	6	±100	±100	±67	±750	±750	±500
12	Asia	Japan	-	Kajima Corp. Ltd.	5 x 5	50	6	±200	±200	±100	±1000	±1000	±500
13	Asia	Japan	-	Kumagai-Gumi Corp Ltd	5 x 5	64	6	±80	±260	±50	±600	±1500	±500
14	Asia	Japan	-	NIED (Nat. Inst. for Disaster Prevention)	6 x 6	1100	3	±1000	?	?	±2000	?	?
15	Asia	Japan	-	Public Works Research Institute (PWRI)	8 x 8	300	6	±600	±600	±300	±2000	±2000	±1000
16	Asia	Japan	-	Tokyu Const. Corp.	4 x 4	30	6	±500	±200	±100	±1500	±1000	?
17	Asia	South Korea	-	Korea Institute of Machinery and Metals, Changwon	4 x 4	30	6	±200	±200	±134	±750	±750	±500
18	Asia	Korea	-	Pusan National University	4 x 4	30	6	±300	±200	±150	±1500	±1500	±1000
19	Asia	Taiwan	-	National Center for Research in Earthquake Engineering	5 x 5	50	6	±250	±100	±100	±1000	±600	±500
20	Europe	France	-	Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA), AZALEE	6 x 6	100	6	±125	±125	±100	±700	±700	±700
21	Europe	Germany		iABG, Ottobrunn	4.1 x 3.2	10	6	±125	±125	±50	±430	±530	±260
22	Europe	Greece	-	National Technical University of Athens	4 x 4	10	6	±100	±100	±100	±1000	±1000	±1000
23	Europe	Italy	-	ENEA (Casaccia R. C.) - System 1, Shake Table (1 of 2)	4 x 4	30	6	±125	±125	±125	±500	±500	±500
24	Europe	Italy	-	ENEA (Casaccia R. C.) - System 1, Shake Table (2 of 2)	2 x 2	5	6	±150	±150	±150	±1000	±1000	±1000
25	Europe	Italy	-	CESI S.p.A., Static & Dynamic Testing Laboratories, Seriate (BG)	4 x 4	30	6	±100	±100	±100	±440	±440	±440
26	Europe	Italy		Laboratory of Earthquake engineering and Dynamic Analysis (LEDA) - "Kore" University of Enna (2 shaking tables)	4 x 4	60	6	±400	±400	±250	±2200	±2200	±1500
27	Europe	Italy		Laboratory of Earthquake engineering and Dynamic Analysis (LEDA) - "Kore" University of Enna (dual table)	10 x 4	100	6	±400	±400	±250	±1100	±1100	±750
28	Europe	The Netherlands	-	European Space Agency (ESA) ESTEC Test Centre, Noordwijk	5.5 x 5.5	22.5	6	±70	±70	±70	±800	±800	±800
29	Europe	Portugal	-	Laboratorio Nacional de Engenharia Civil (LNEC), Lisbon	5.6 x 5.6	40	3	±175	±175	±175	±200	±200	±200
30	Europe	Russia	-	Hydroproject Research Institute	5 x 5	50	3	±70	±70	±40	±600	?	?
31	Europe	Spain	-	CEDEX, Madrid	3 x 3	10	6	±100	±100	±50	?	?	?
32	Europe	Turkey	-	Bogazici University, Istanbul	0.7 x 0.7	0.1	3	±120	±120	±120	±1200	±1200	±1200
33	Europe	UK	-	University of Bristol (EERC), Bristol	3 x 3	17	6	±150	±150	±150	±1100	±1100	±1100
34	Asia	Pakistan	-	Earthquake Engineering Center, University of Engineering & Technology, Peshawar	6.0 x 6.0	60	6	±300	±300	±300	±1100	±1100	±1100
35	North America	Mexico	Mexico D. F.	Universidad Nacional Autónoma de México (UNAM), México	4 x 4	20	5	±150	±150	±75	±1100	±1100	±450
36	North America	USA	Colorado	ANCO Engineers, Inc Boulder, Colorado	3 x 3	10	3	±200	±200	±200	±2000	±2000	±2000
37	North America	USA	Alabama	Wyle Laboratories	2.7 x 2.7	4.5	3	±250	±250	±250	±1120	±1120	±1120
38	North America	USA	California	University of California at Berkeley, PEER-UCB lab	6.1 x 6.1	85	6	±127	±127	±51	±762	±762	±254
39	North America	USA	California	University of California at Berkeley, Structures Laboratory on main campus	3.3 x 2.6	10	1	±800	n/a	n/a	±2540	n/a	n/a
40	North America	USA	California	University of California at San Diego	12.2 x 7.6	2000	1	±750	n/a	n/a	±1800	n/a	n/a
41	North America	USA	Pennsylvania	Clark Testing, Jefferson Hills	3.7 x 3.7	17.2	3	±152	±152	±152	±1270	±1270	±1270
42	North America	USA	New York	University at Buffalo (State University of New York)	3.6 x 3.6	50	6	±150	±150	±75	±1250	±1250	±500
43	North America	USA	Nevada	University of Nevada at Reno (6 axis table)	2.75 x 2.75	50	6	±75	±300	±100	?	?	?
44	North America	USA	Nevada	Dynamic Certification Laboratories	2.0 diam.	4.5	6	±140	±120	±150	±1000	±1000	±1200
45	North America	USA	Virginia	AREVA, Inc Lynchburg, Virginia	3 x 3	10	6	±142	±142	±142	±1778	±1778	±1778
46	North America	USA	Maryland	Morgan State University	3 x 3	10	6	±254	±508	±152.4	±1000	±1000	-
47	South East Asia	Vietnam	Ha Noi		3 x 3	10	6	±142	±142	±142	±1778	±1778	±1778

The displacement limitations of the shaking tables that are listed in Table 3-1 are going to control the filtering requirements. They are combined in several groups and summarized in Figure 3-1.

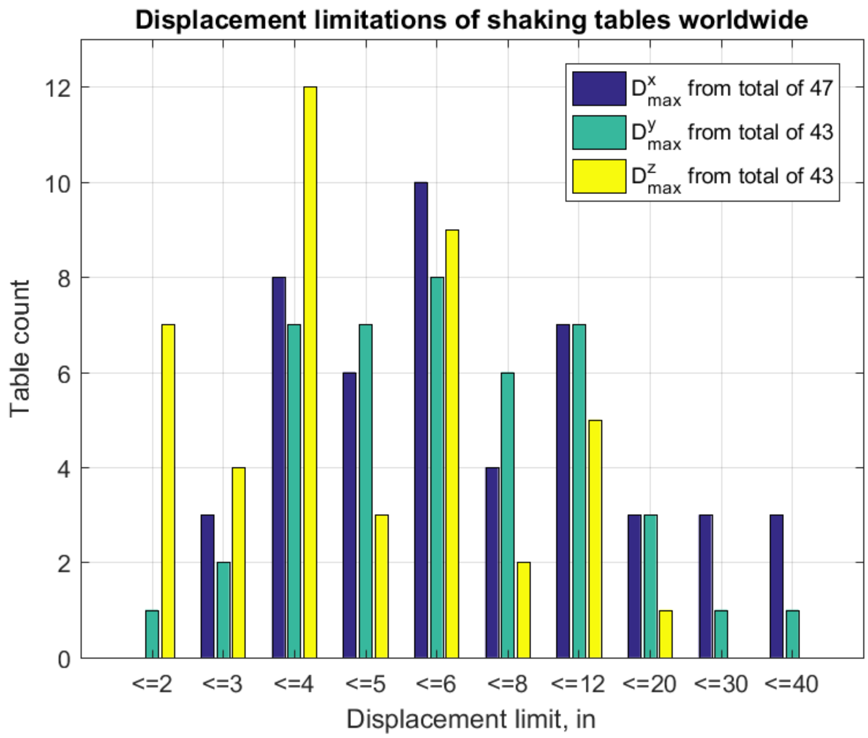


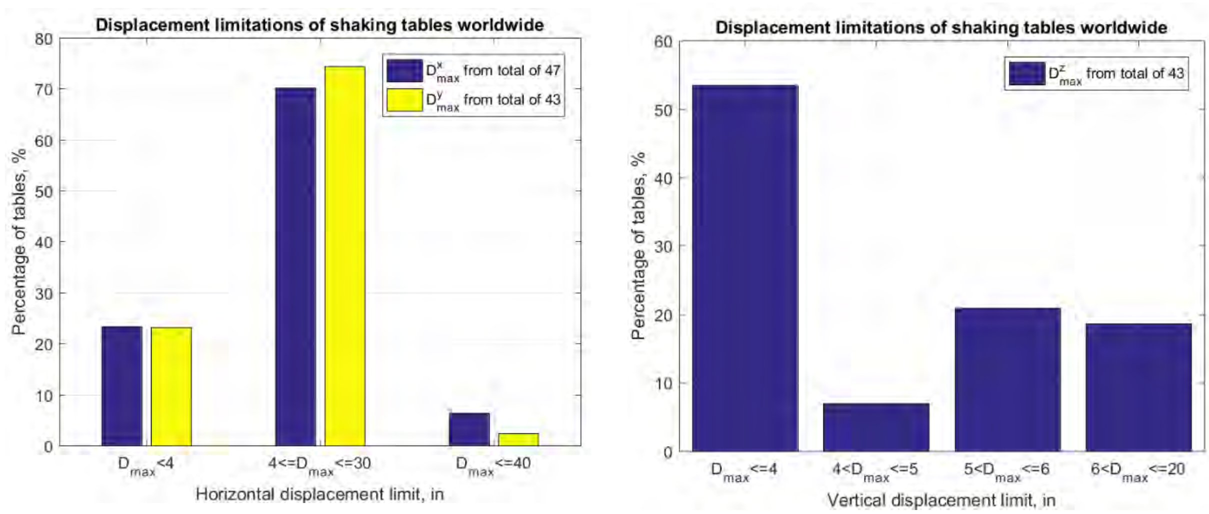
Figure 3-1. Summary of the displacement limitations of shaking tables worldwide

The validation tests of the time histories started at the uni-axial shaking table at the University of California, Berkeley with a stroke capacity of ±31.5 inches and peak velocity of 100 in/sec. The time histories were filtered to accommodate this stroke limitation and all validation tests were successful (Takhirov et al, 2017a and 2017b). In addition, several testing laboratories worldwide were approached to validate the time histories on their shaking tables. The list included the following labs: shaking table laboratory at Bristol University (Bristol, United Kingdom), shaking table laboratory at National Technical University of Athens (Athens, Greece), Clark Testing (Jefferson Hills, Pennsylvania, USA), shaking table laboratory at PEER-UCB (Richmond, California, USA), shaking table laboratory at iABG lab (Ottobrunn, Germany), shaking testing laboratory at the University of Nevada, Reno (Reno, Nevada, USA), the shaking table facility at the State University of New York at Buffalo (Buffalo, New York, USA), uni-axial shaking table laboratory at Istanbul Technical University (Istanbul, Turkey), shaking table facility at University of Pavia (Pavia, Italy) and many others. The main concern raised by the labs was that the time histories require application of a filtering procedure that can vary from facility to facility and it would be more convenient for the labs and the engineering community to have several filtered options of the time histories suitable for the majority of the shaking tables worldwide.

The filtering procedure used in the past (Takhirov et al, 2005) was utilized herein. The main goal was to develop a complete set for three types of time histories: (1) modified from a record obtained during crustal type earthquake; (2) modified from a record obtained during subduction type earthquake; and (3) synthetically generated time history. The results are presented in Table 3-2 which shows the stroke limitations they are filtered for and the file names containing the filtered time histories. The complete sets were developed for TestQke4IEEE5-4 (yellow fields), TestQke4IEEE5-5 (orange fields) and TestQke4IEEE5-6 (green fields).

The filtered versions of the time histories can be deployed at most of the shaking tables worldwide as presented in Figure 3-2. For example, since the filtered time histories cover many displacement thresholds in horizontal directions up to 30 in, they can be successfully used at more than 90% of the shaking tables worldwide (a sum of the two first columns in Figure 3-2– left). The filtered versions of the vertical time histories can be used at more than 80% of the shaking tables worldwide (a sum of the three first columns in Figure 3-2– right).

The following example shows how the filtered time histories can be selected from Table 3-2 for a particular shaking table. For example, the shaking table at the Pacific Earthquake Engineering Research Center, the University of California, Berkeley has ±5 in displacement limitation in both horizontal directions and ±2 in displacement limitation in the vertical direction. Therefore, the correct selection of the filtered versions of the IEEE-spectrum compatible time histories is as follows: TestQke4IEEE5-4X-0p785hz-4p887in.xlsx, TestQke4IEEE5-4Y-0p855hz-4p808in.xlsx, and TestQke4IEEE5-4Z-1p235hz-1p982in.xlsx for X, Y, and Z directions, respectively.



a) Limitations in horizontal directions

b) Limitations in vertical directions

Figure 3-2. Percentage of the major shaking tables within certain limitation groups

Appendix B presents acceleration, velocity and displacement plots for all filtered versions. The spectral plot for each component of the time history is presented at the bottom. This plot also shows the frequency from which the enveloping of the IEEE693 starts.

All time histories including their filtered versions will be posted on the Internet by the IEEE693 Working Group. They can be downloaded free of charge from the following link: http://ewh.ieee.org/cmte/substations/scd0/wgd4/basefile.htm.

Table 3-2. List of IEEE693-spectrum-compatible time histories filtered to meet limitations of majority of shaking tables

	Displacement limit of shaking table						
TestQke	≤ 30in (750 mm)	≤ 8in (200 mm)	≤ 6in (150 mm)	≤ 5in (125 mm)	≤ 4in (100 mm)	≤ 3in (75 mm)	≤ 2in (50 mm)
TestQke4IEEE5-4X.AT2	TestQke4IEEE5-4X-0p150hz-28p650in.xlsx	TestQke4IEEE5-4X-0p585hz-7p806in.xlsx	TestQke4IEEE5-4X-0p665hz-5p694in.xlsx	TestQke4IEEE5-4X-0p785hz-4p887in.xlsx	TestQke4IEEE5-4X-0p980hz-3p870in.xlsx		
TestQke4IEEE5-4Y.AT2	TestQke4IEEE5-4Y-0p155hz-29p040in.xlsx	TestQke4IEEE5-4Y-0p572hz-7p704in.xlsx	TestQke4IEEE5-4Y-0p800hz-5p751in.xlsx	TestQke4IEEE5-4Y-0p855hz-4p808in.xlsx	TestQke4IEEE5-4Y-0p965hz-3p878in.xlsx		
TestQke4IEEE5-4Z.AT2			TestQke4IEEE5-4Z-0p665hz-5p733in.xlsx	TestQke4IEEE5-4Z-0p785hz-4p860in.xlsx	TestQke4IEEE5-4Z-0p885hz-3p897in.xlsx	TestQke4IEEE5-4Z-0p950hz-2p963in.xlsx	TestQke4IEEE5-4Z-1p235hz-1p982in.xlsx
TestQke4IEEE5-5X.AT2	TestQke4IEEE5-5X-0p175hz-29p628in.xlsx	TestQke4IEEE5-5X-0p560hz-7p764in.xlsx	TestQke4IEEE5-5X-0p665hz-5p826in.xlsx	TestQke4IEEE5-5X-0p805hz-4p866in.xlsx	TestQke4IEEE5-5X-0p880hz-3p811in.xlsx		
TestQke4IEEE5-5Y.AT2	TestQke4IEEE5-5Y-0p130hz-29p645in.xlsx	TestQke4IEEE5-5Y-0p550hz-7p753in.xlsx	TestQke4IEEE5-5Y-0p770hz-5p752in.xlsx	TestQke4IEEE5-5Y-0p795hz-4p829in.xlsx	TestQke4IEEE5-5Y-0p900hz-3p920in.xlsx		
TestQke4IEEE5-5Z.AT2			TestQke4IEEE5-5Z-0p685hz-5p846in.xlsx	TestQke4IEEE5-5Z-0p750hz-4p880in.xlsx	TestQke4IEEE5-5Z-0p650hz-3p899in.xlsx	TestQke4IEEE5-5Z-0p760hz-2p800in.xlsx	TestQke4IEEE5-5Z-0p980hz-1p852in.xlsx
TestQke4IEEE5-6X.AT2	TestQke4IEEE5-6X-0p175hz-29p623in.xlsx	TestQke4IEEE5-6X-0p540hz-7p619in.xlsx	TestQke4IEEE5-6X-0p635hz-5p416in.xlsx	TestQke4IEEE5-6X-0p695hz-4p496in.xlsx	TestQke4IEEE5-6X-0p860hz-3p765in.xlsx		
TestQke4IEEE5-6Y.AT2	TestQke4IEEE5-6Y-0p130hz-29p587in.xlsx	TestQke4IEEE5-6Y-0p410hz-7p894in.xlsx	TestQke4IEEE5-6Y-0p755hz-5p530in.xlsx	TestQke4IEEE5-6Y-0p790hz-4p873in.xlsx	TestQke4IEEE5-6Y-0p850hz-3p842in.xlsx		
TestQke4IEEE5-6Z.AT2			TestQke4IEEE5-6Z-0p570hz-5p743in.xlsx	TestQke4IEEE5-6Z-0p630hz-4p753in.xlsx	TestQke4IEEE5-6Z-0p775hz-3p705in.xlsx	TestQke4IEEE5-6Z-0p985hz-2p816in.xlsx	TestQke4IEEE5-6Z-0p980hz-1p963in.xlsx

4 Conclusions

In this study, the seed motions were matched to the target IEEE693 spectrum within a tight tolerance and four three-component IEEE693-spectrum-compatible time histories from historic records were developed. Three seed motions were selected from the set of crustal records and one seed motion was selected from the set of subduction records. The spectral accelerations of the time histories fit into 16% and 15% strips enveloping the IEEE693 spectrum at $1/24^{th}$ and $1/12^{th}$ octave resolutions, respectively. The same tolerance was achieved for three three-component synthetic IEEE693-spectrum-compatible strong motions developed in the study. This suite of seven time histories is proposed for use in the IEEE693 seismic qualification testing and analysis. All time histories developed in this project satisfy the requirements of IEEE P693/D16. Users should note that TestQke4IEEE5-5 was developed from a seed motion recorded from a subduction earthquake. Although it satisfies the requirements of IEEE P693/D16 and may be used for qualification activities, its main purpose is to aid research in the behavior and performance of equipment in subduction earthquakes, which are specifically not addressed in IEEE P693/D16. Further research is planned in this area.

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Takhirov, S.M., Fujisaki, E., Kempner, L., Riley M., and Low, B. 2017c. Development of Time Histories for IEEE693 Testing and Analysis (Including Seismically Isolated Equipment), Pacific Earthquake Engineering Research Center, University of California at Berkeley, PEER 2017/10, December 2017.

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Appendix A: Plots of Unfiltered Time Histories: Acceleration, Velocity, Displacement and Spectra

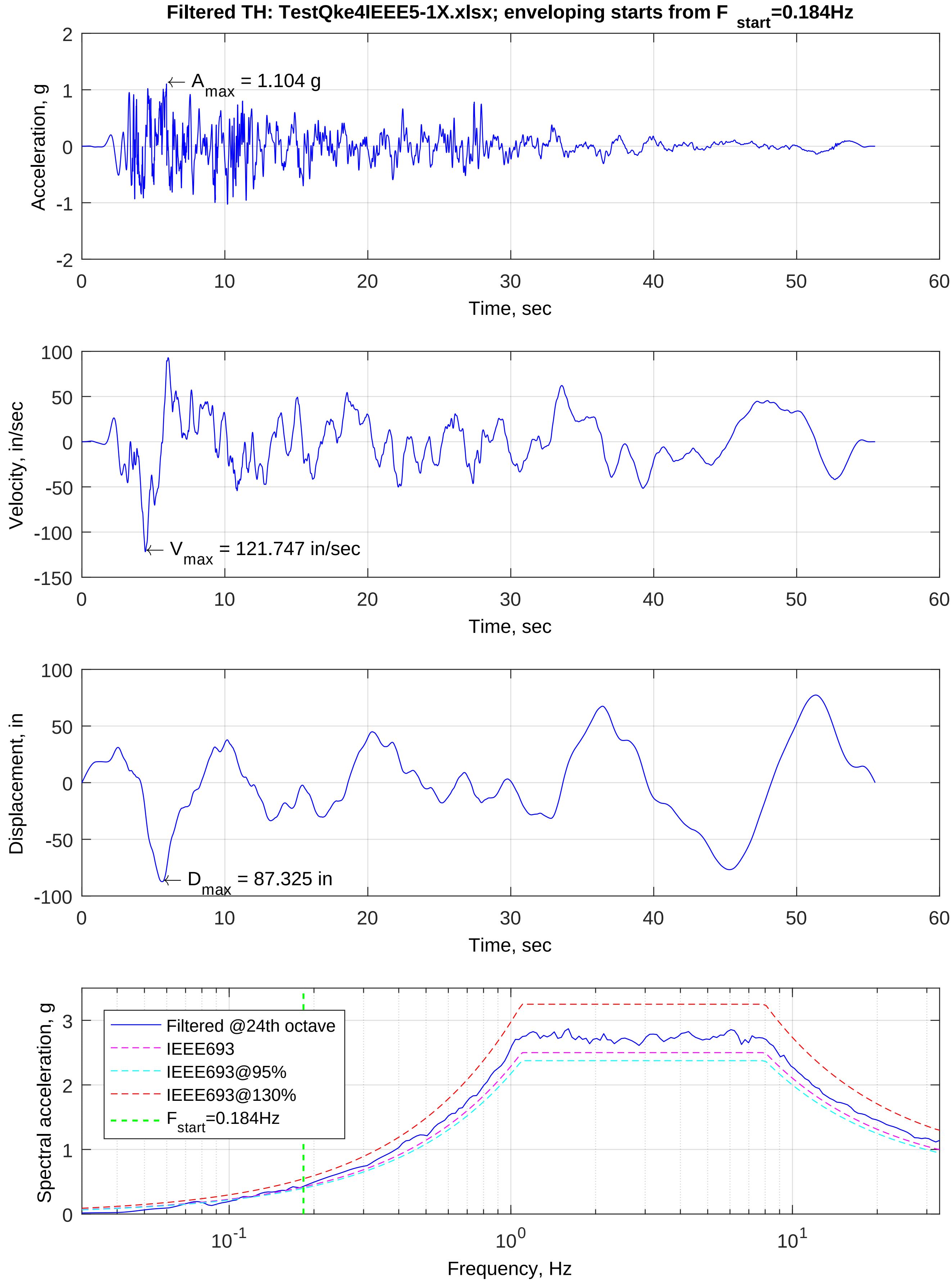


Figure A-1. Summary plots for TestQke4IEEE5-1X.xlsx

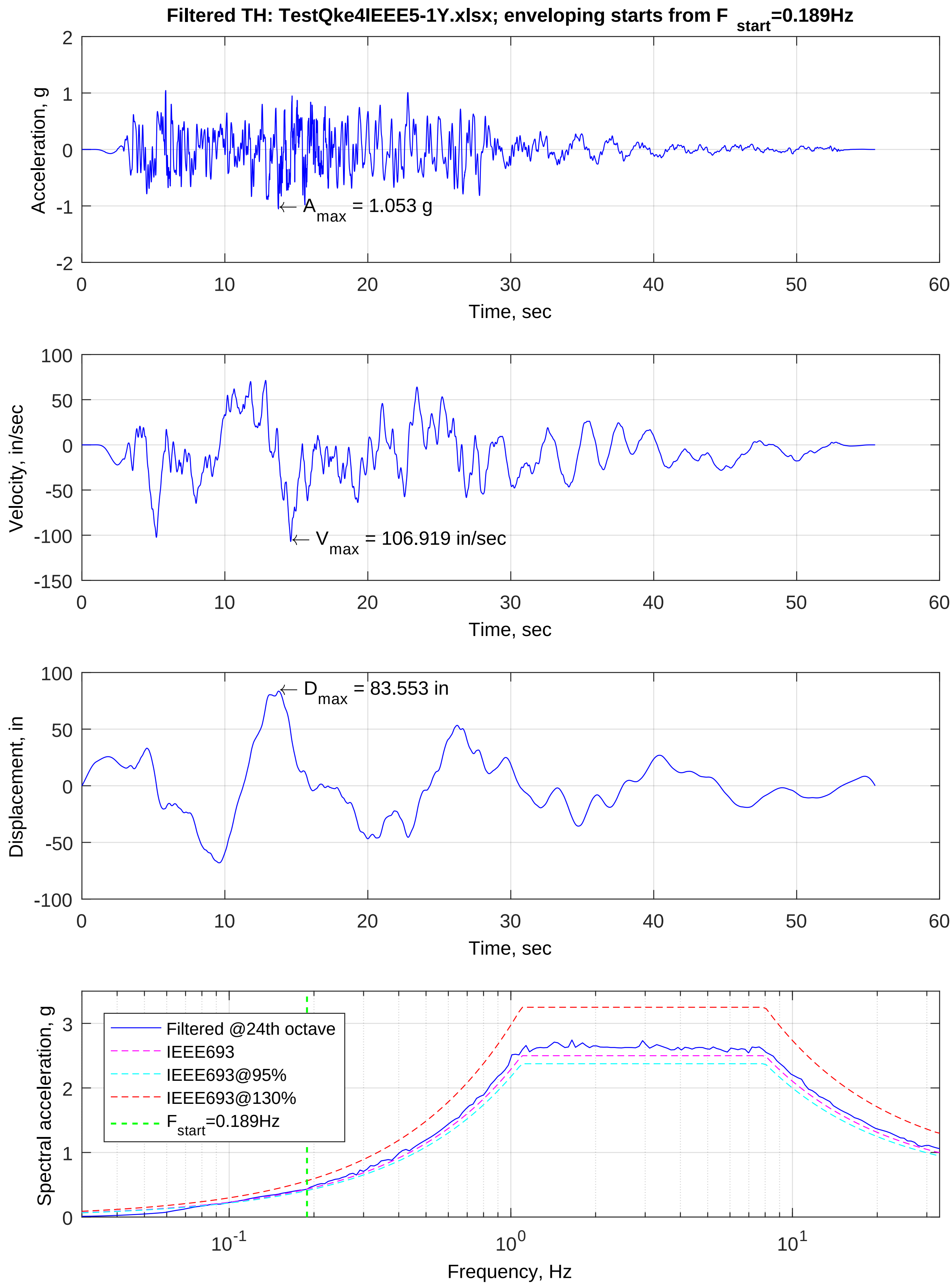


Figure A-2. Summary plots for TestQke4IEEE5-1Y.xlsx

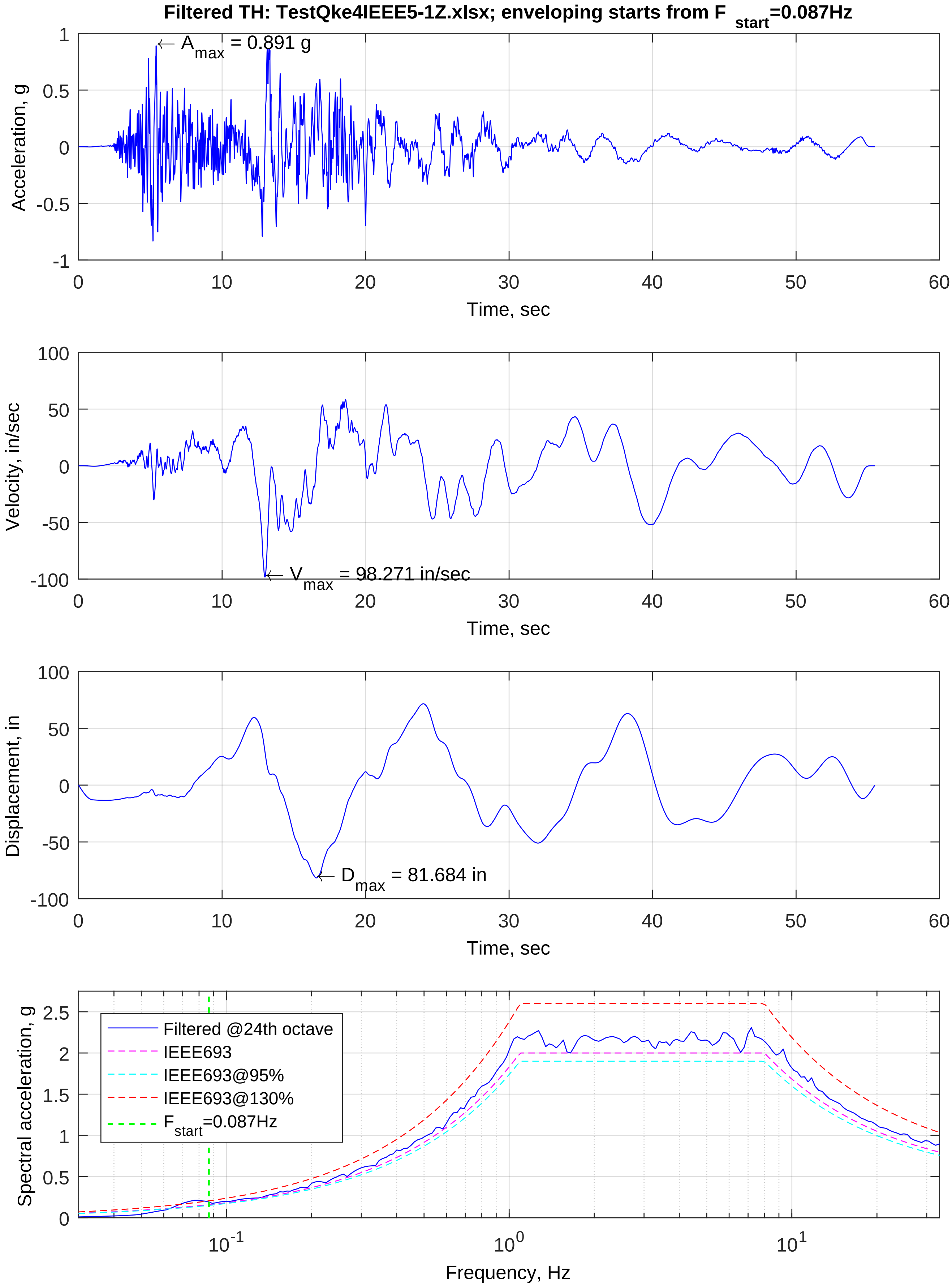


Figure A-3. Summary plots for TestQke4IEEE5-1Z.xlsx

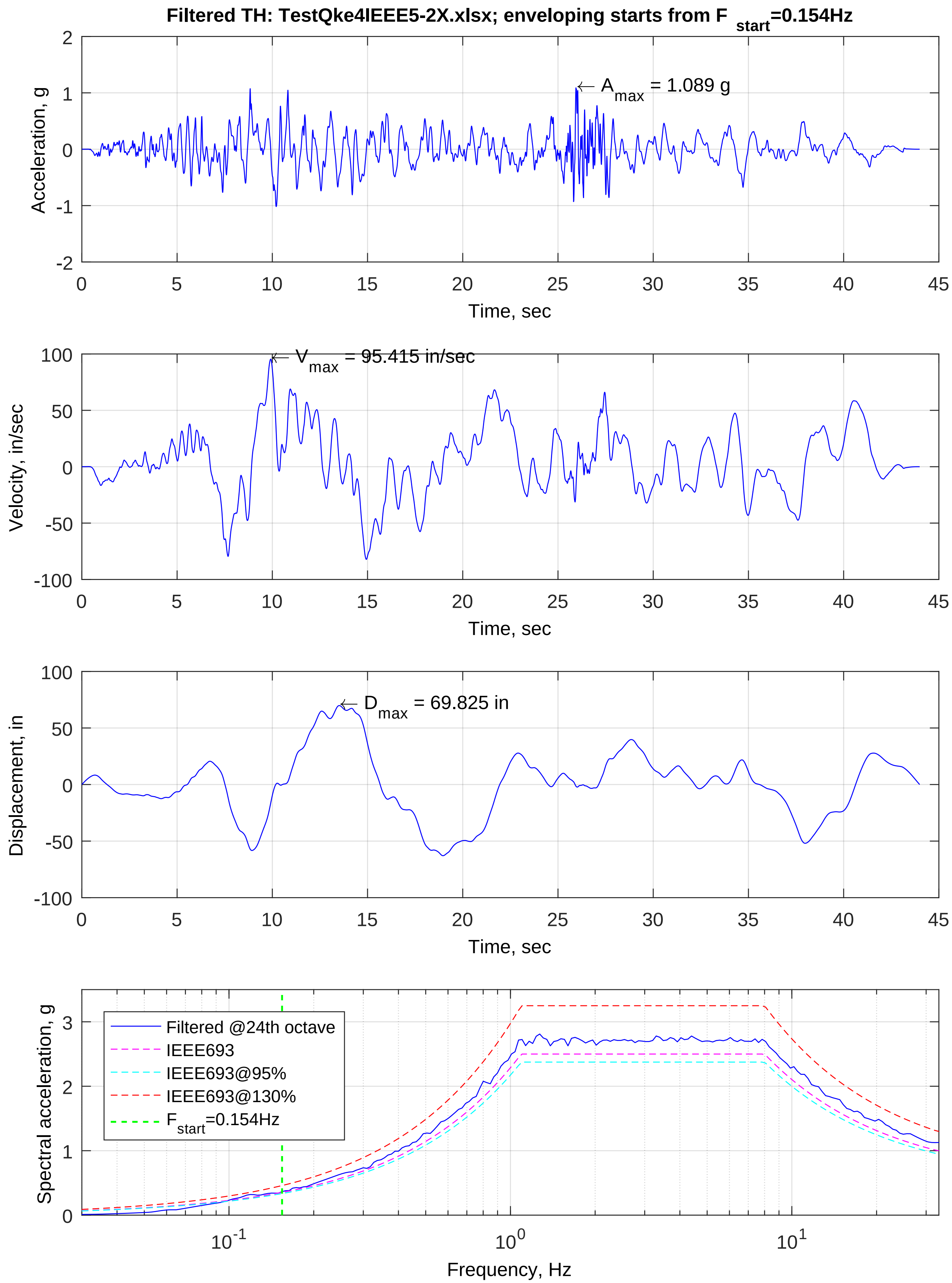
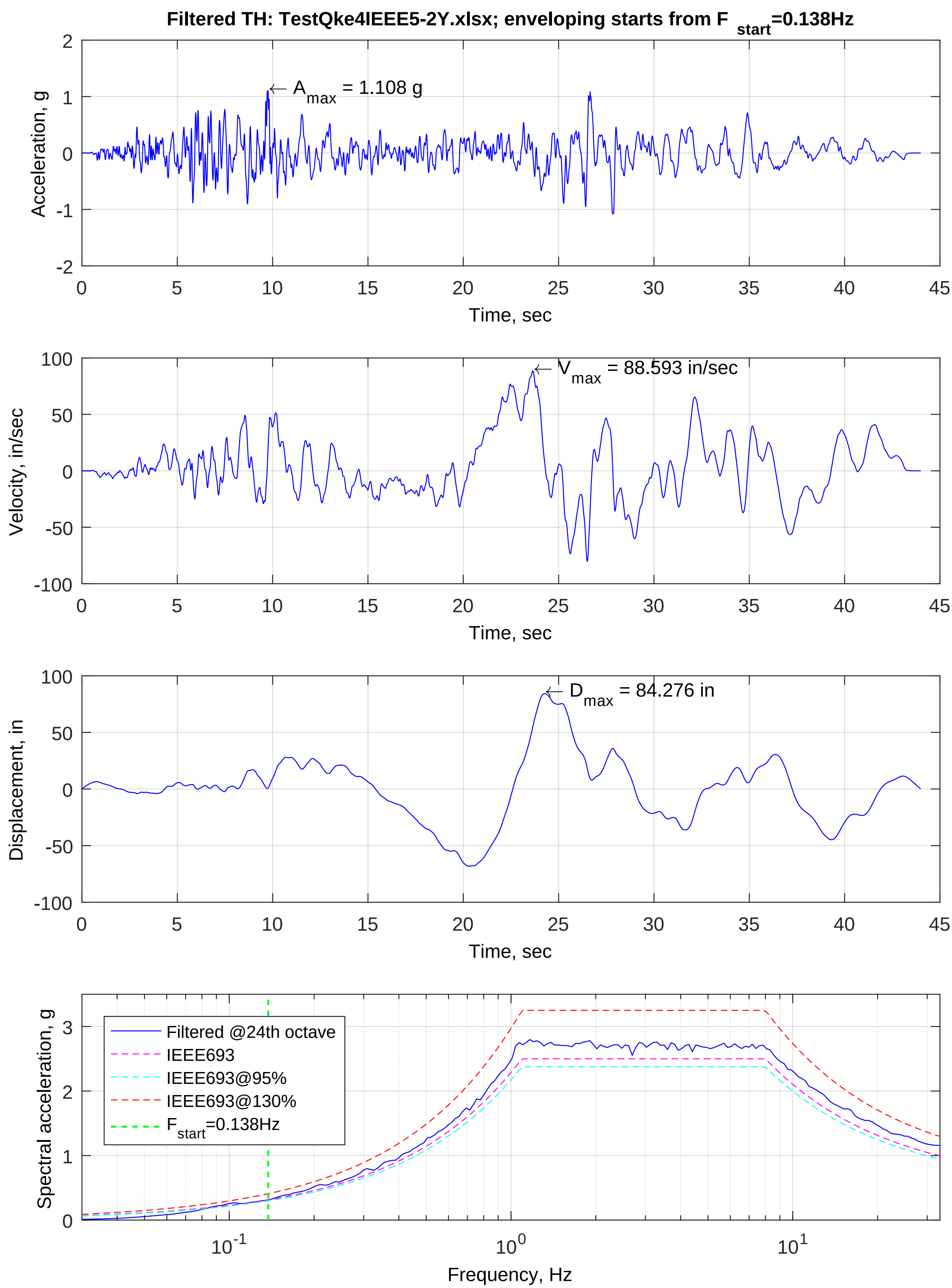


Figure A-4. Summary plots for TestQke4IEEE5-2X.xlsx



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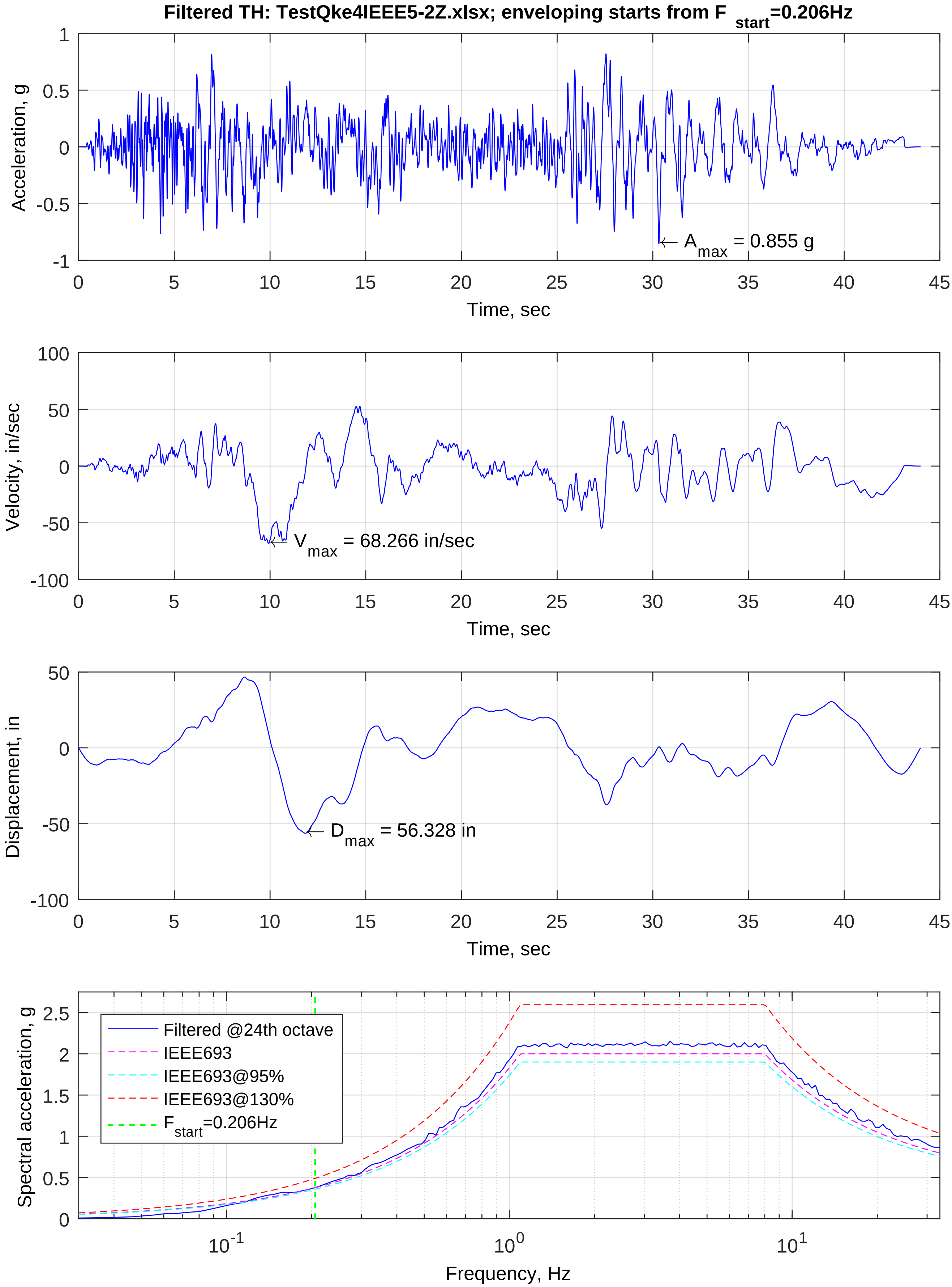

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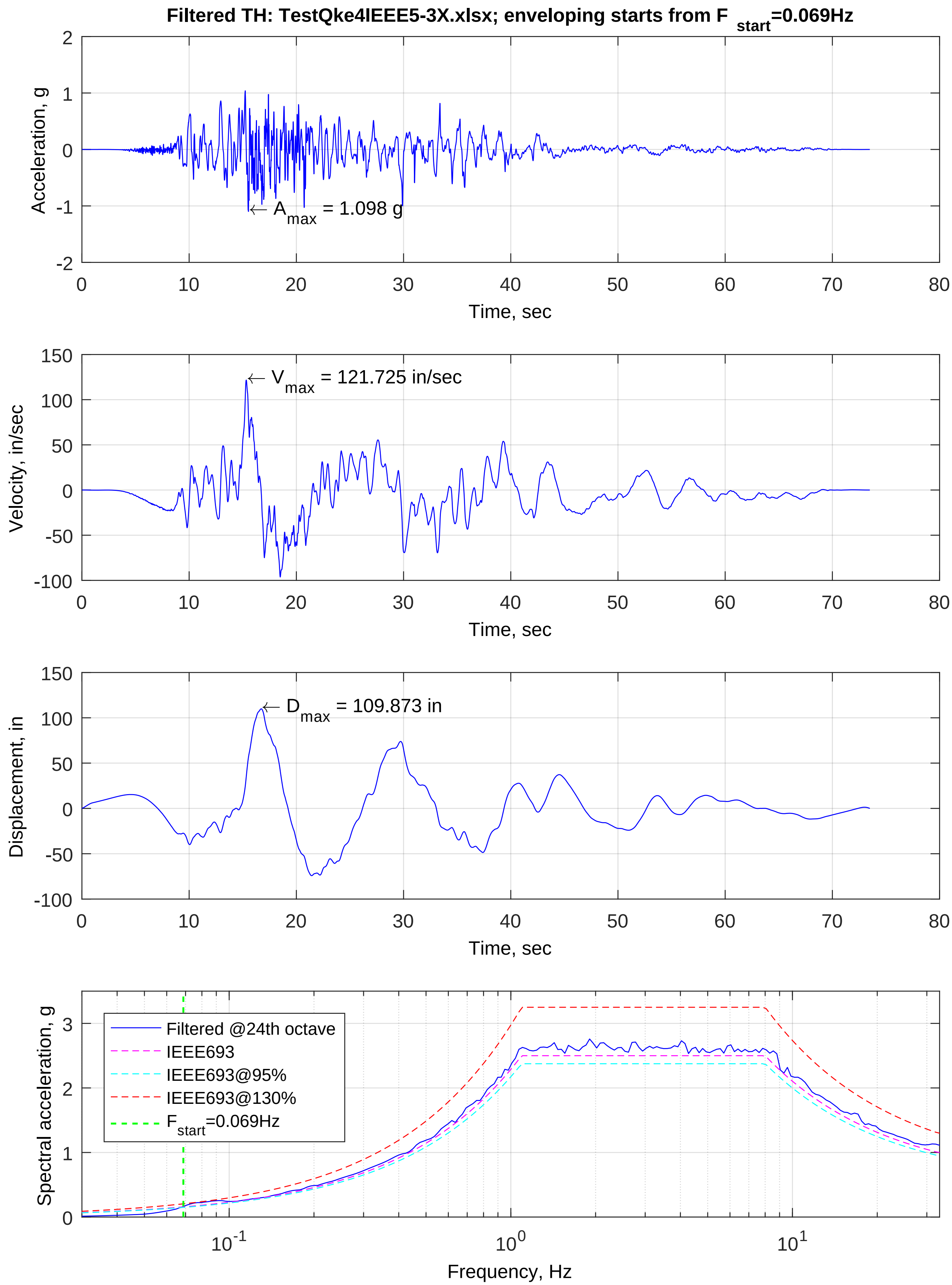

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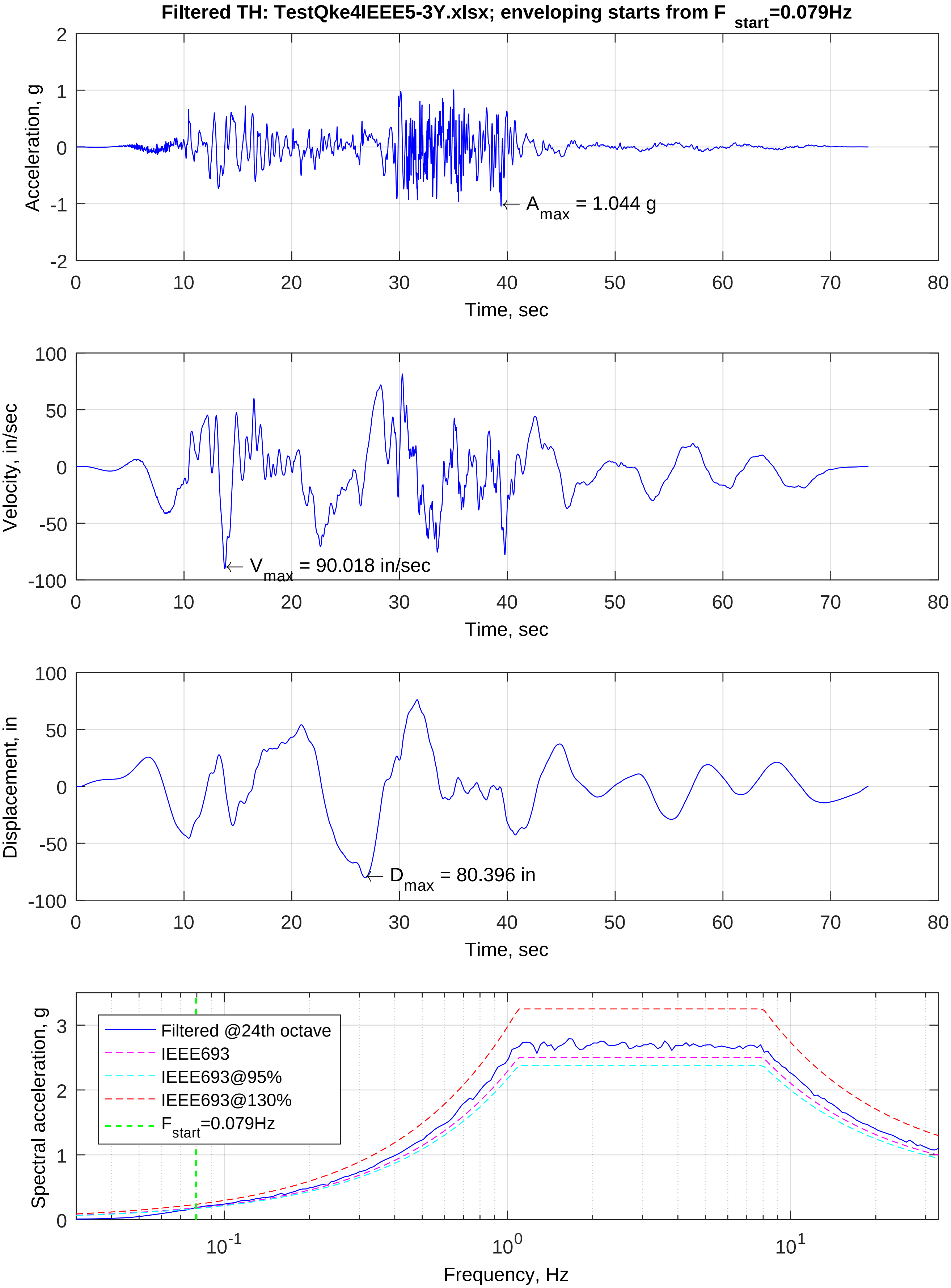


Figure A-8. Summary plots for TestQke4IEEE5-3Y.xlsx

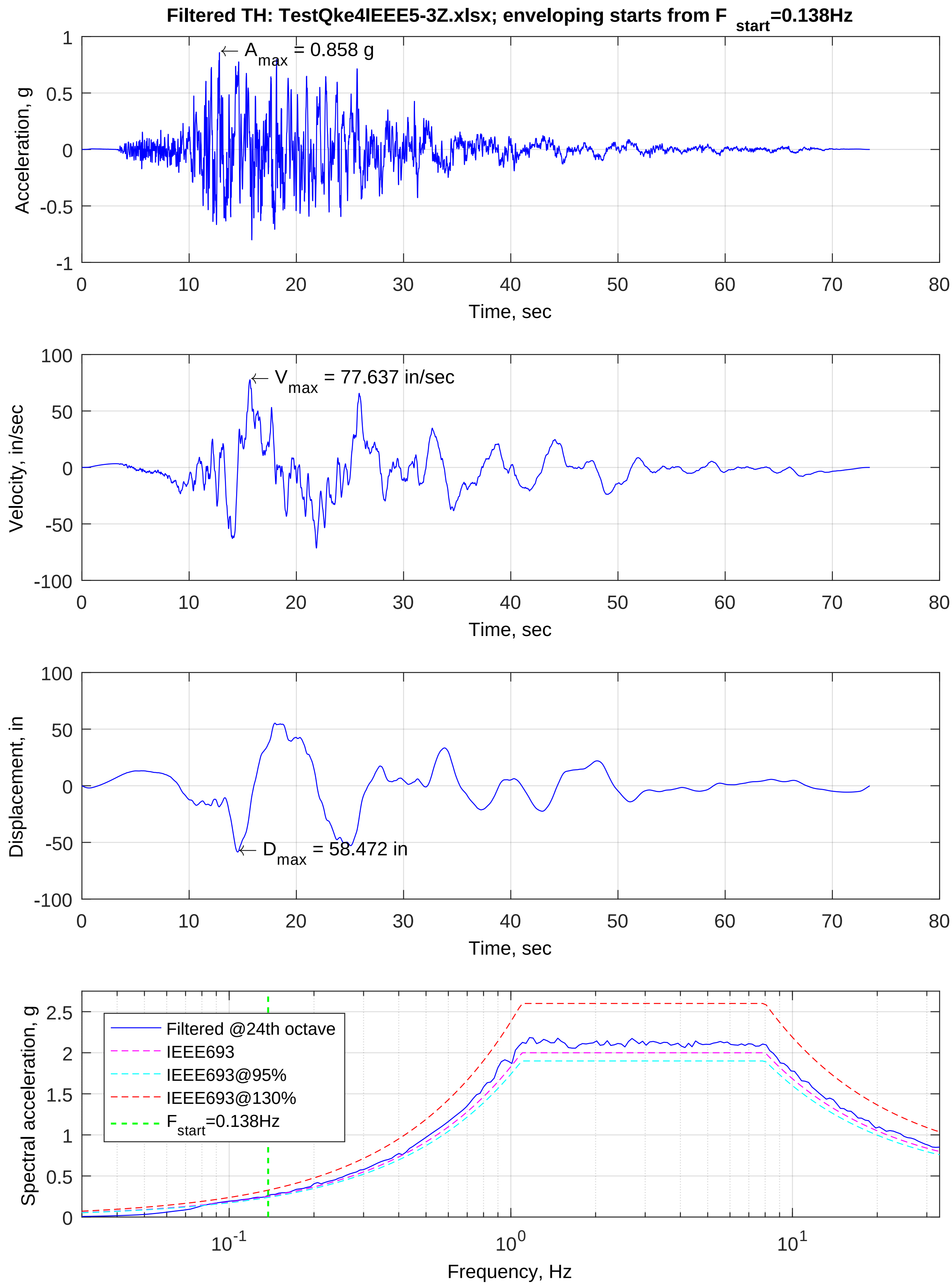
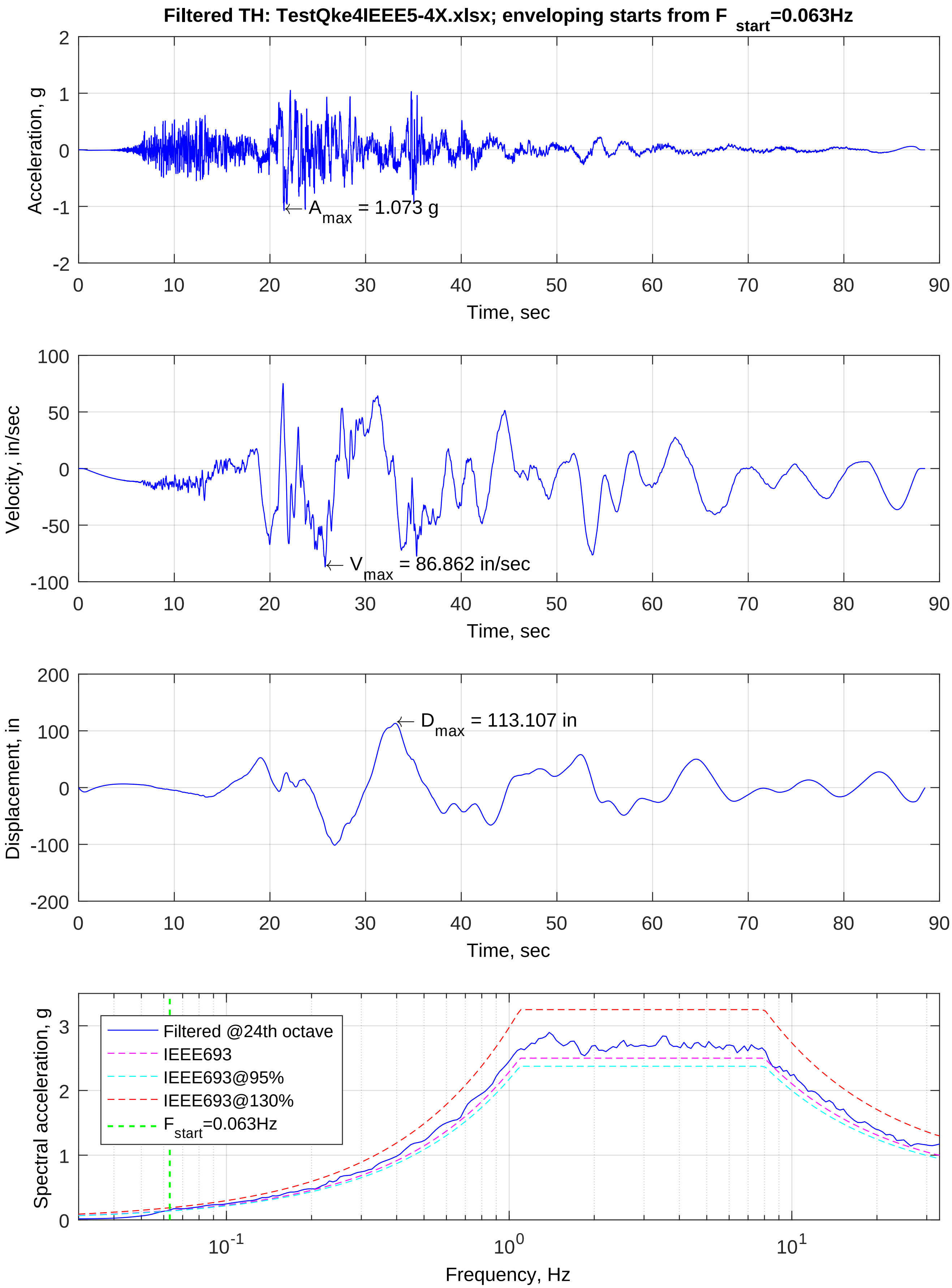


Figure A-9. Summary plots for TestQke4IEEE5-3Z.xlsx



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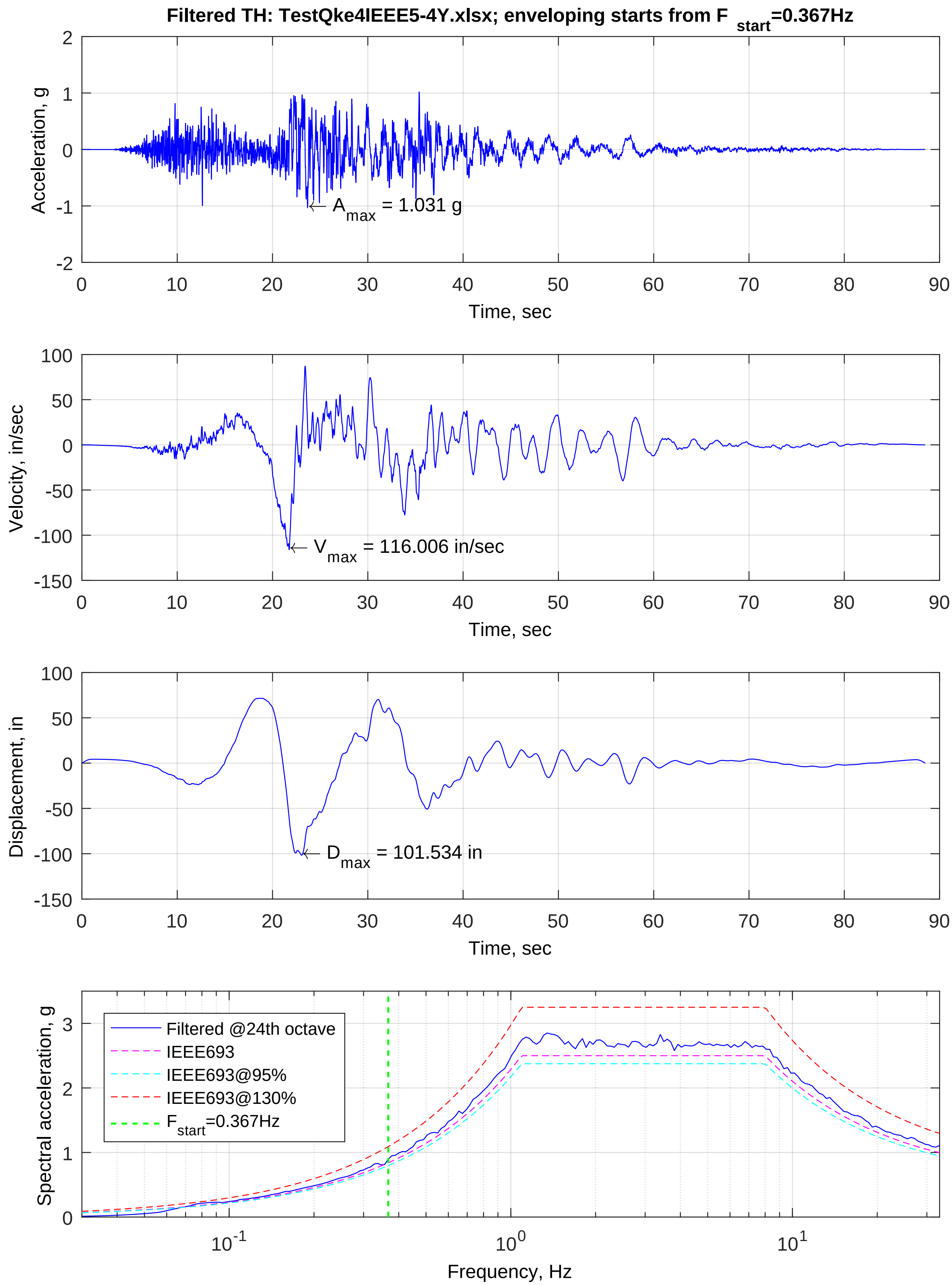

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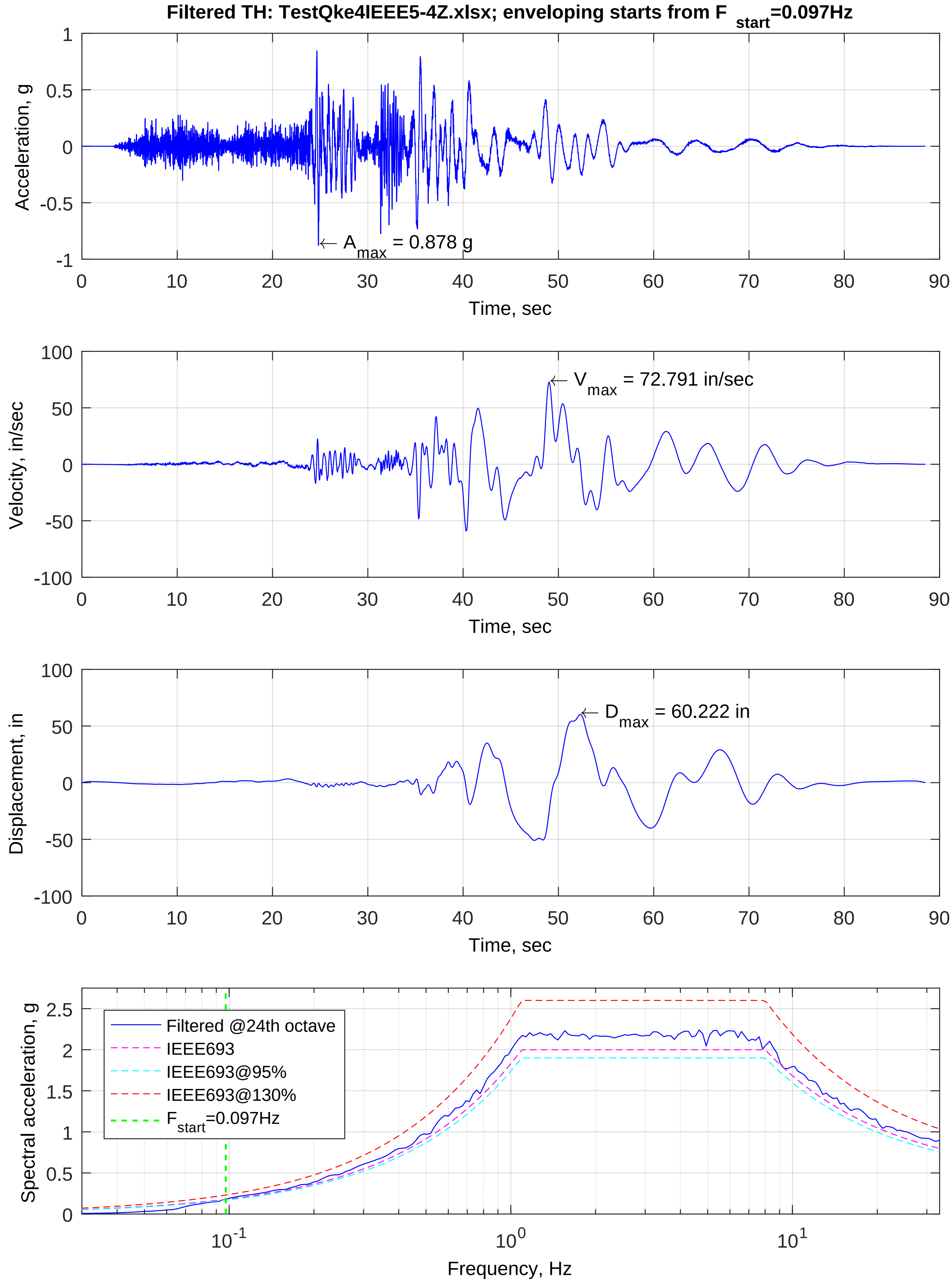

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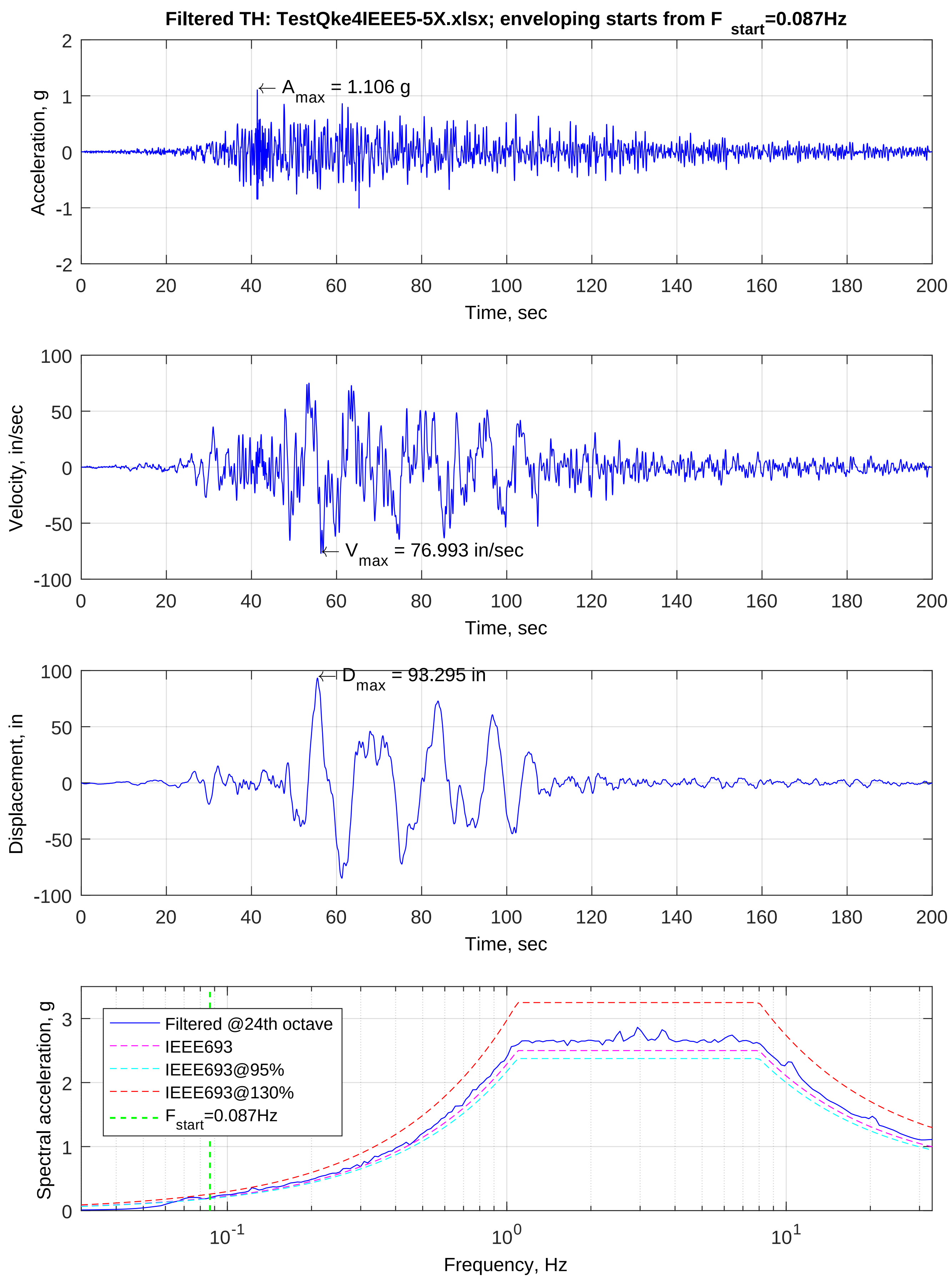

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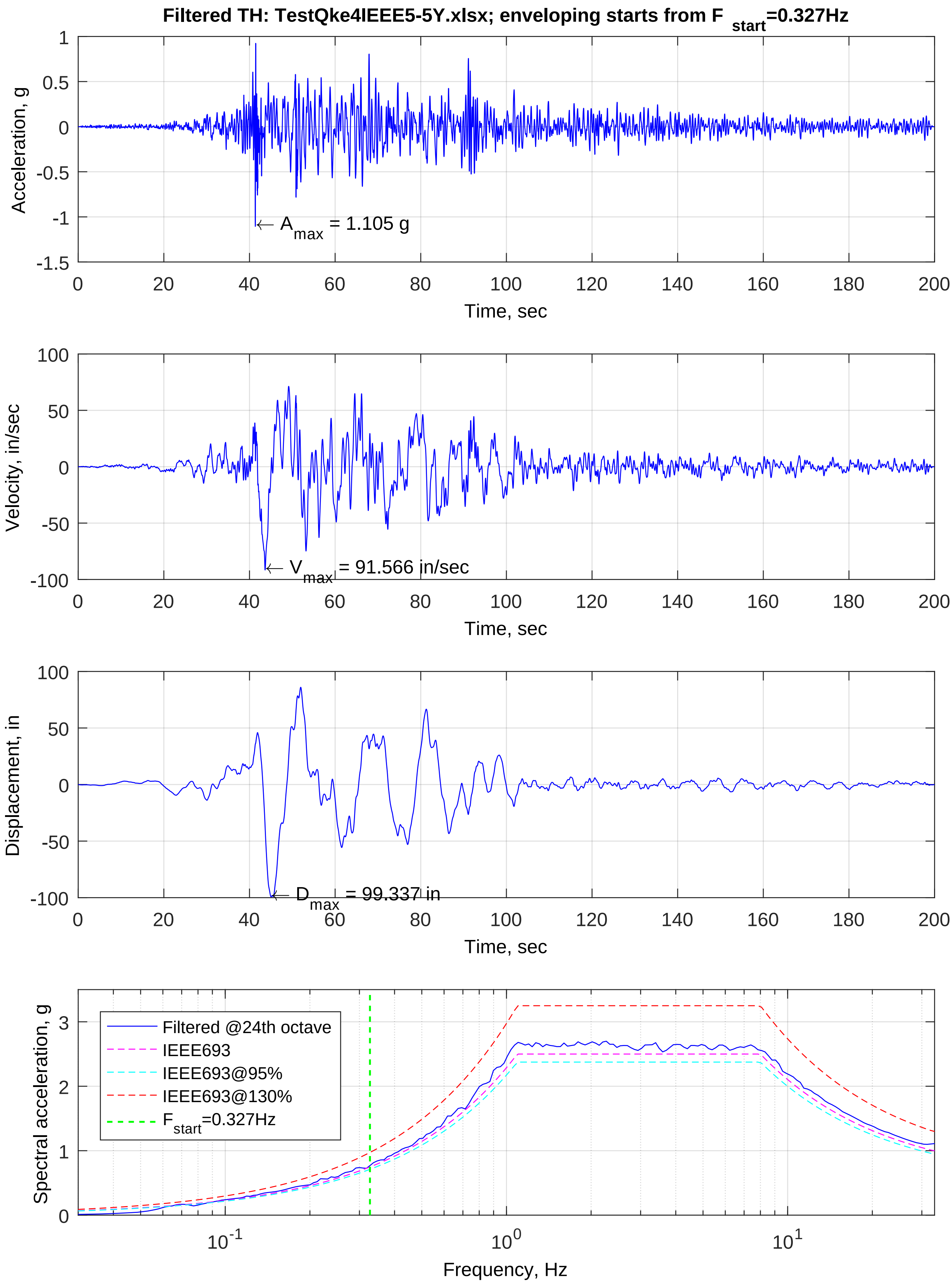
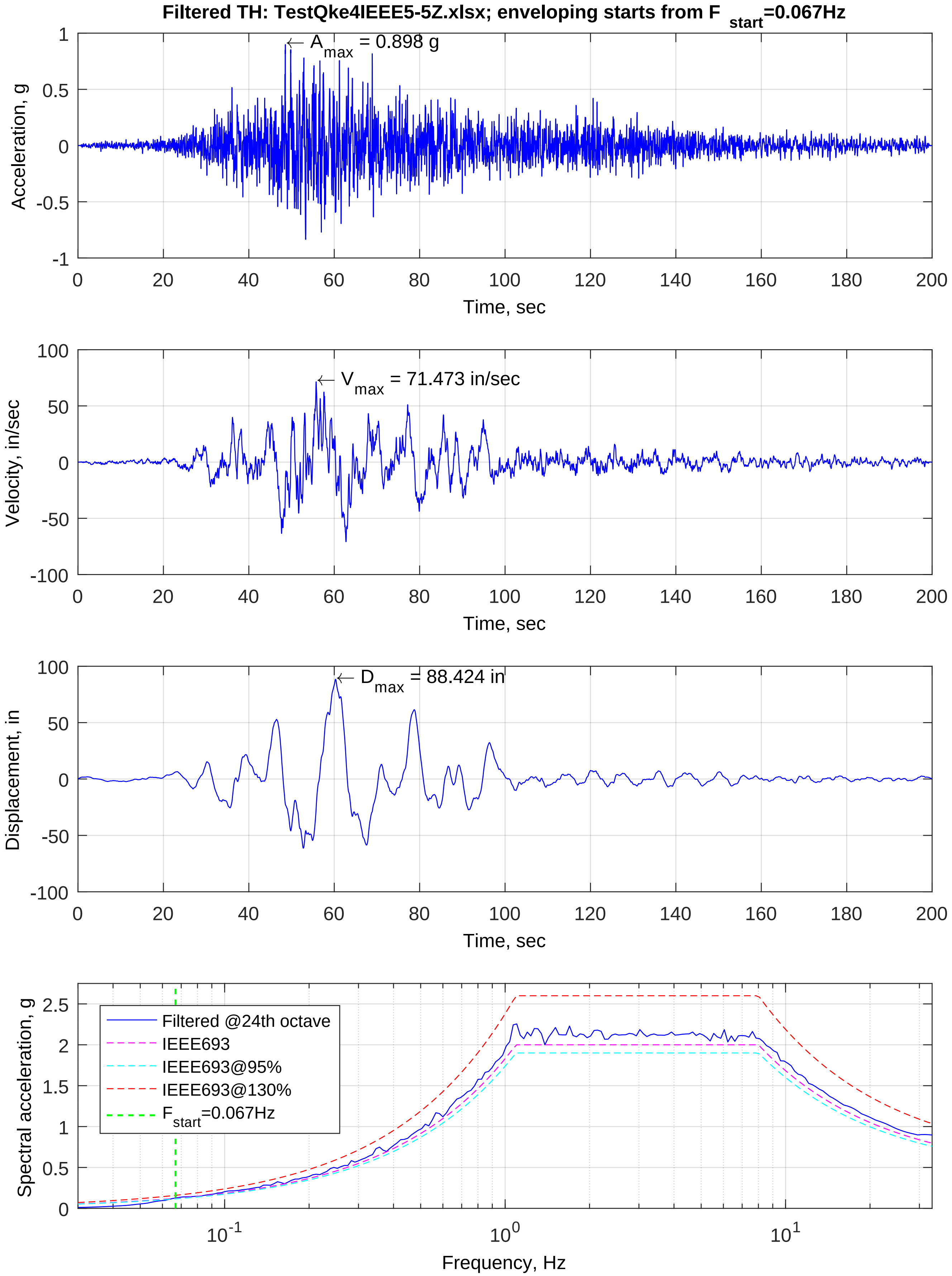


Figure A-14. Summary plots for TestQke4IEEE5-5Y.xlsx



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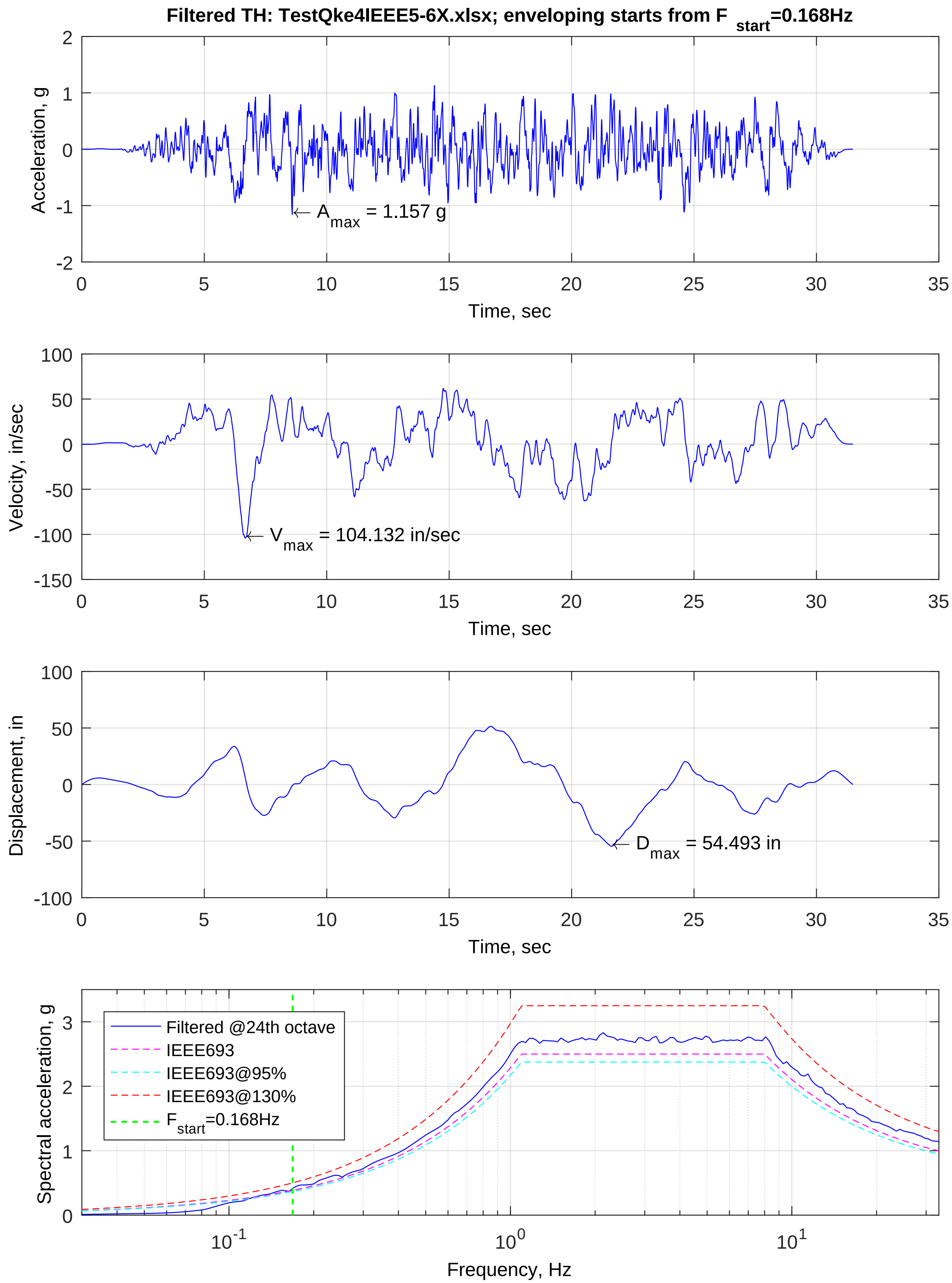

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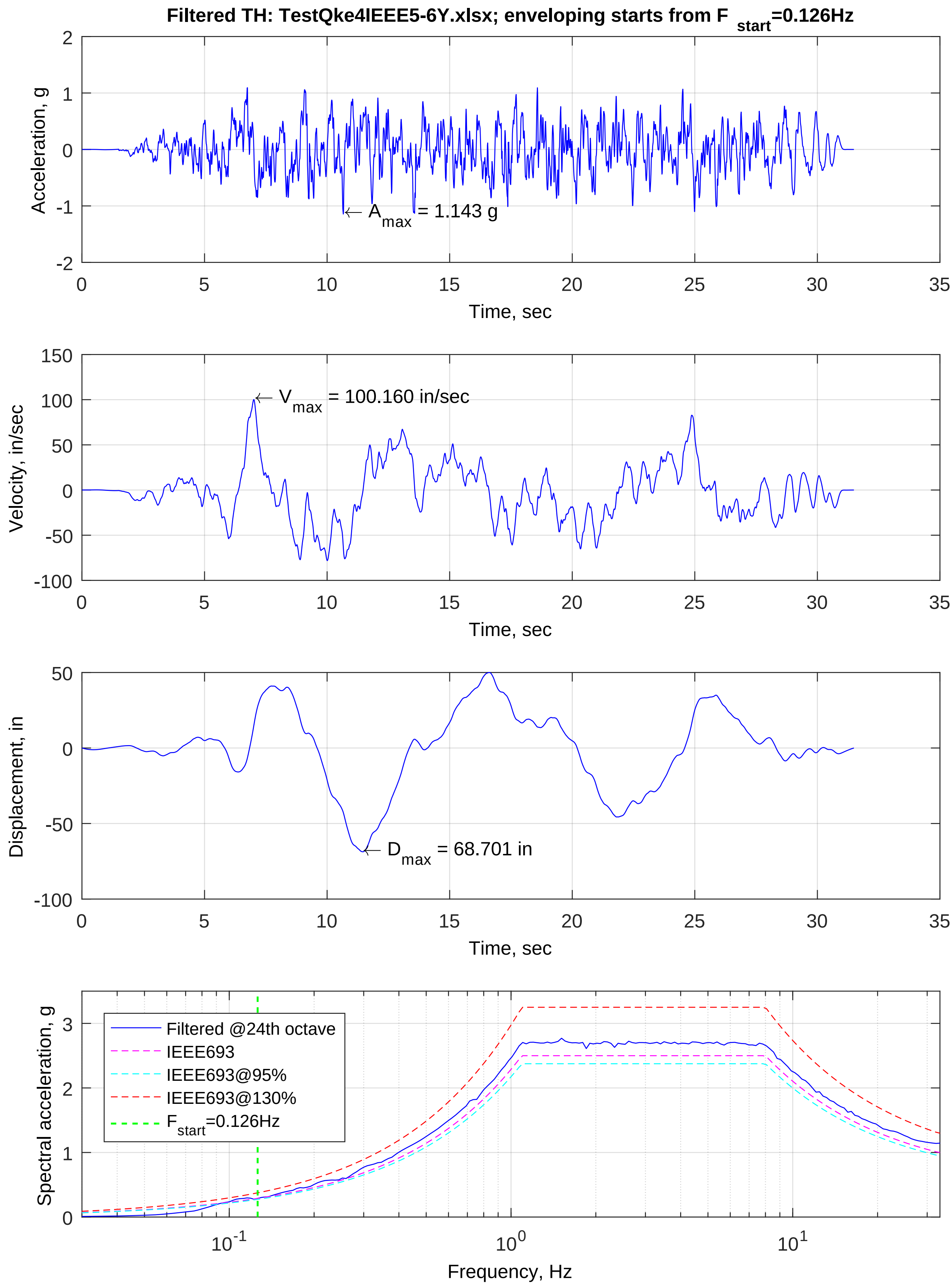

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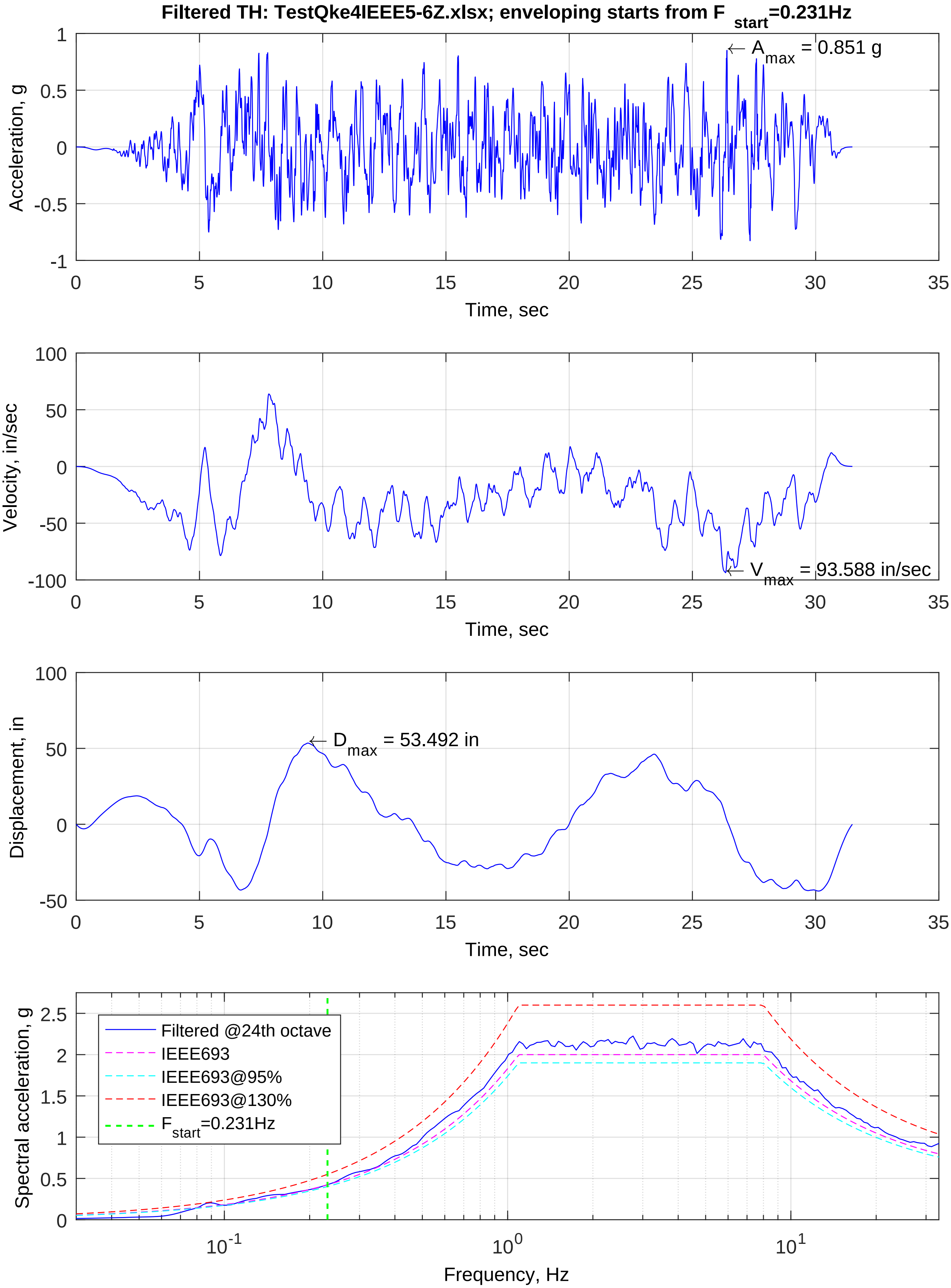

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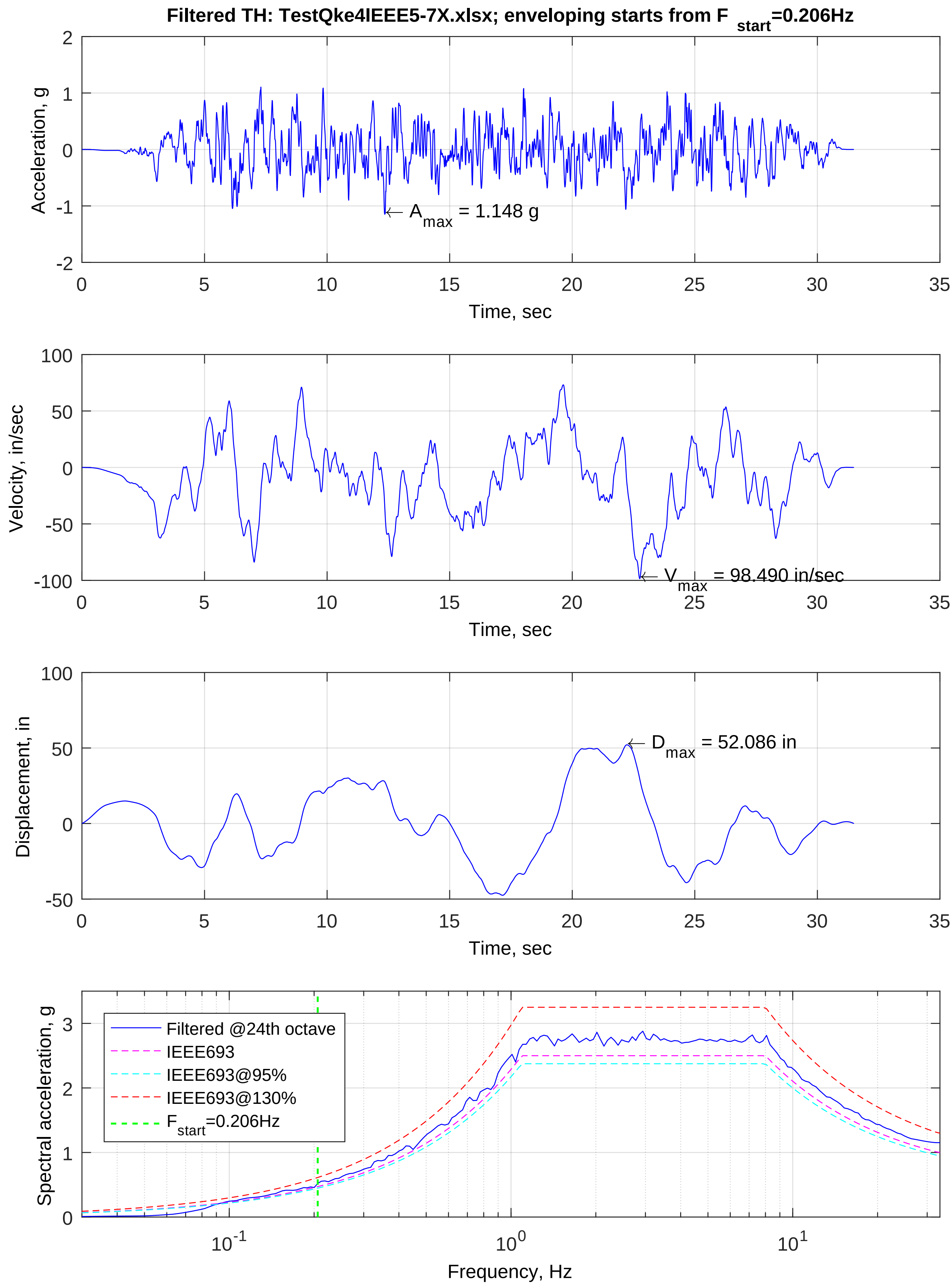

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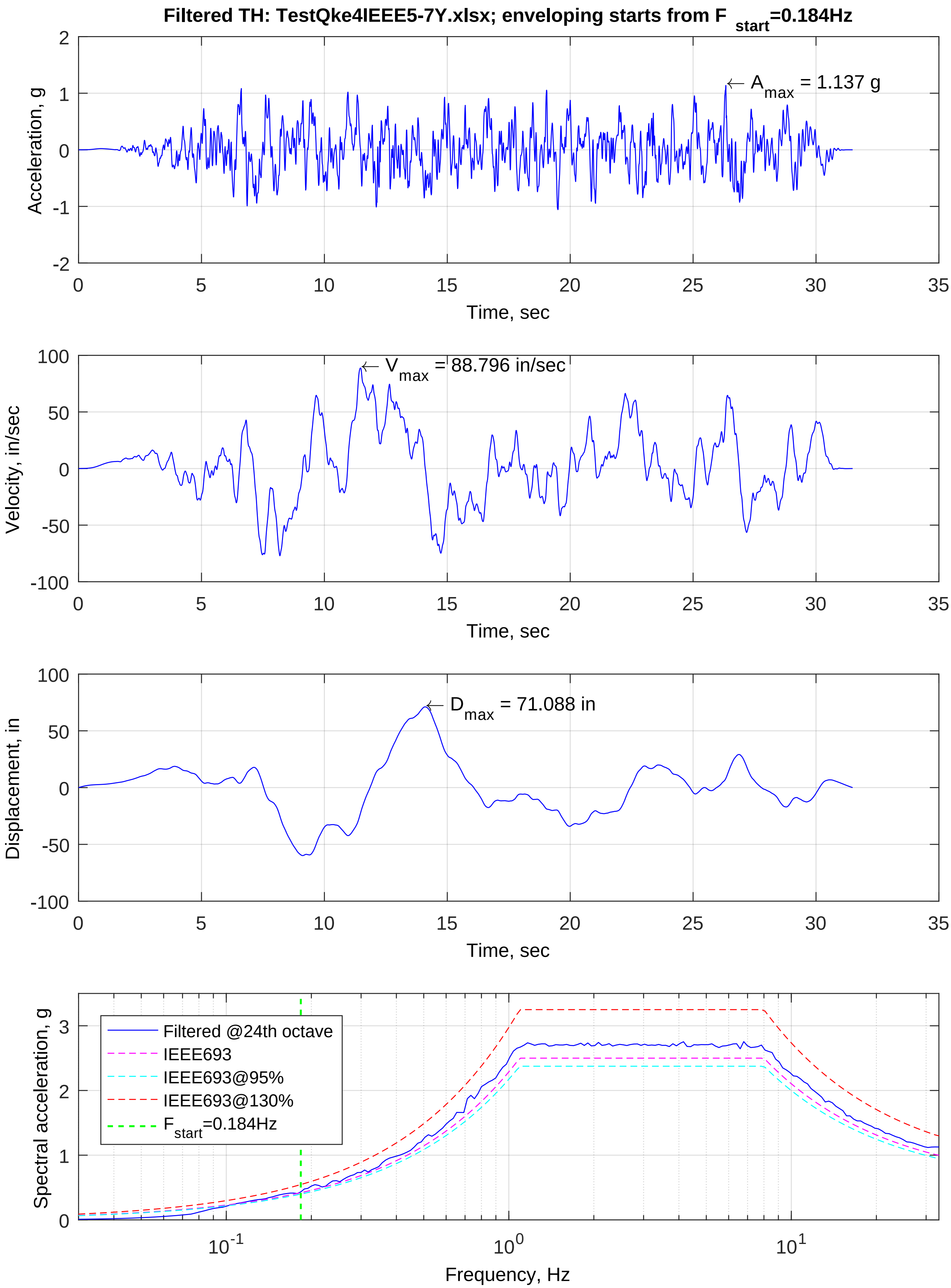

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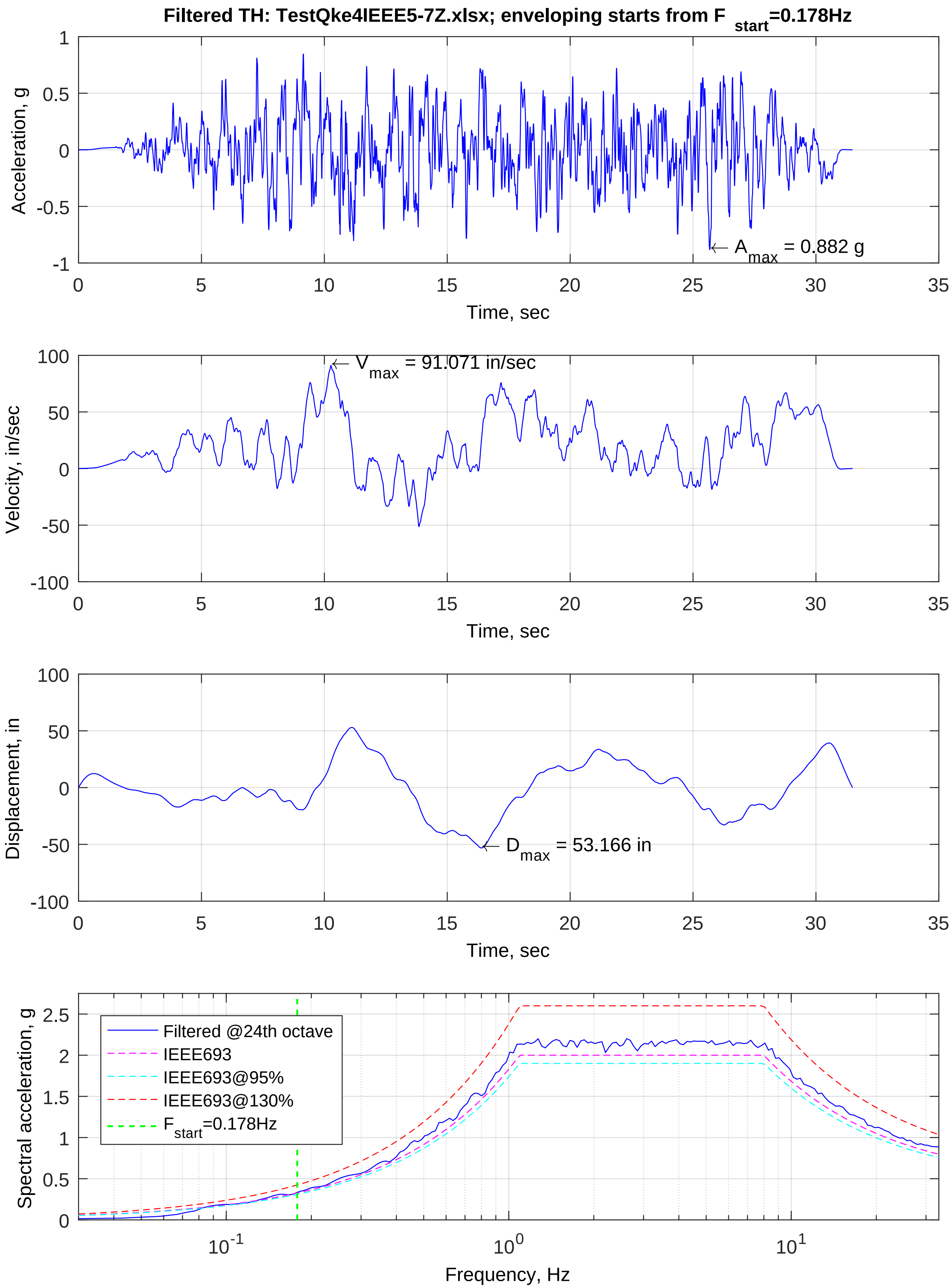

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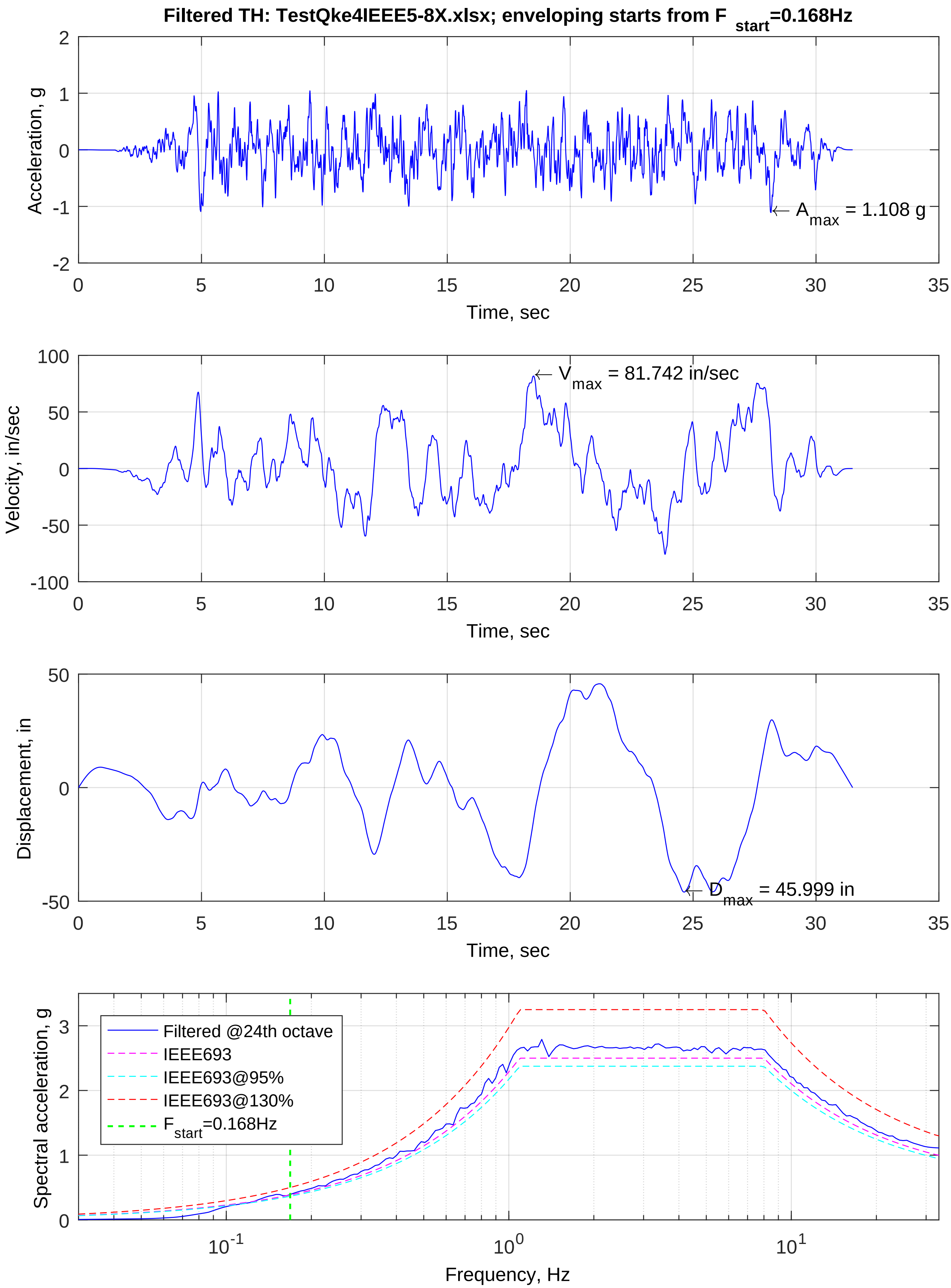

Figure A-22. Summary plots for TestQke4IEEE5-8X.xlsx

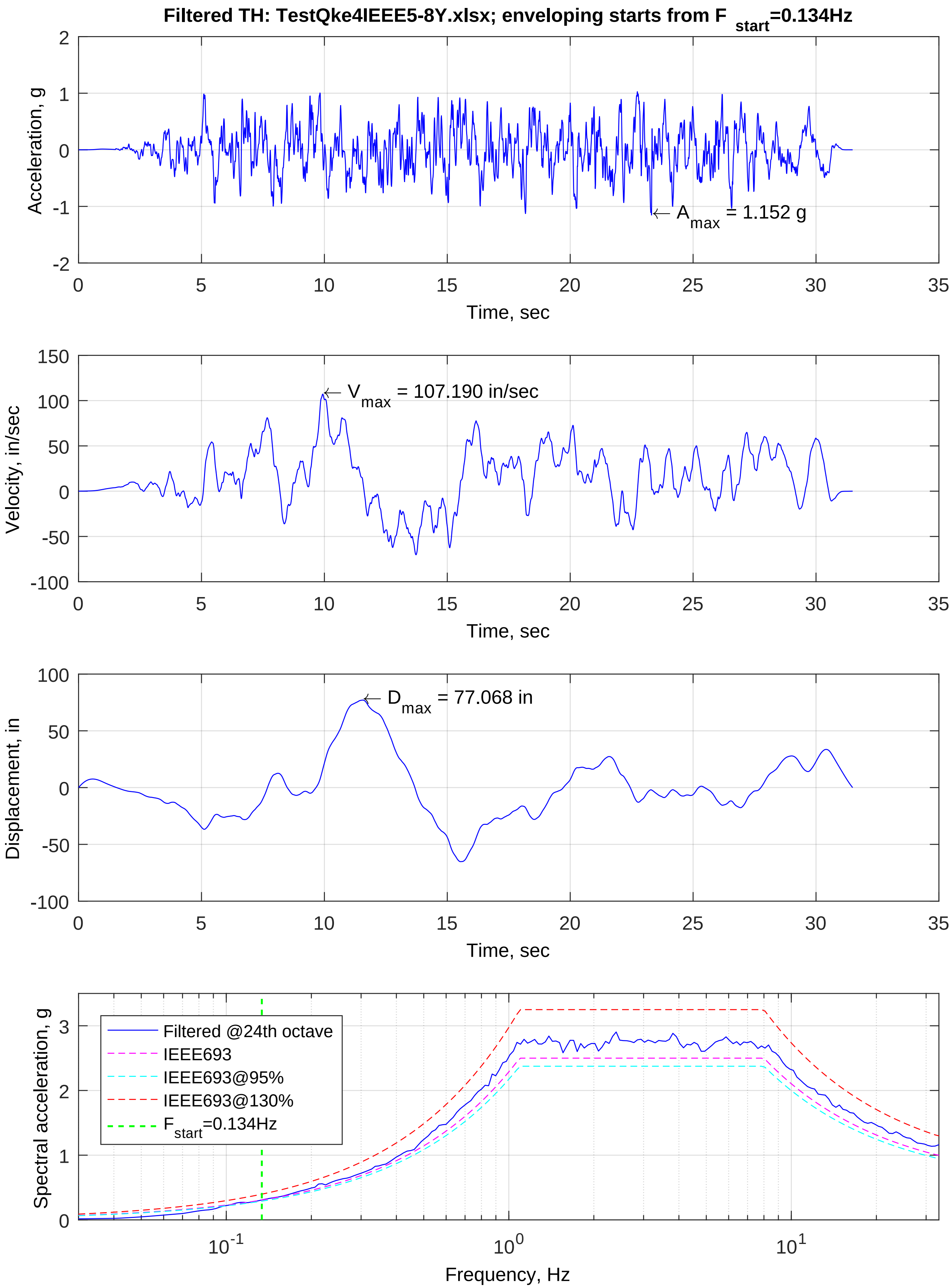

Figure A-23. Summary plots for TestQke4IEEE5-8Y.xlsx

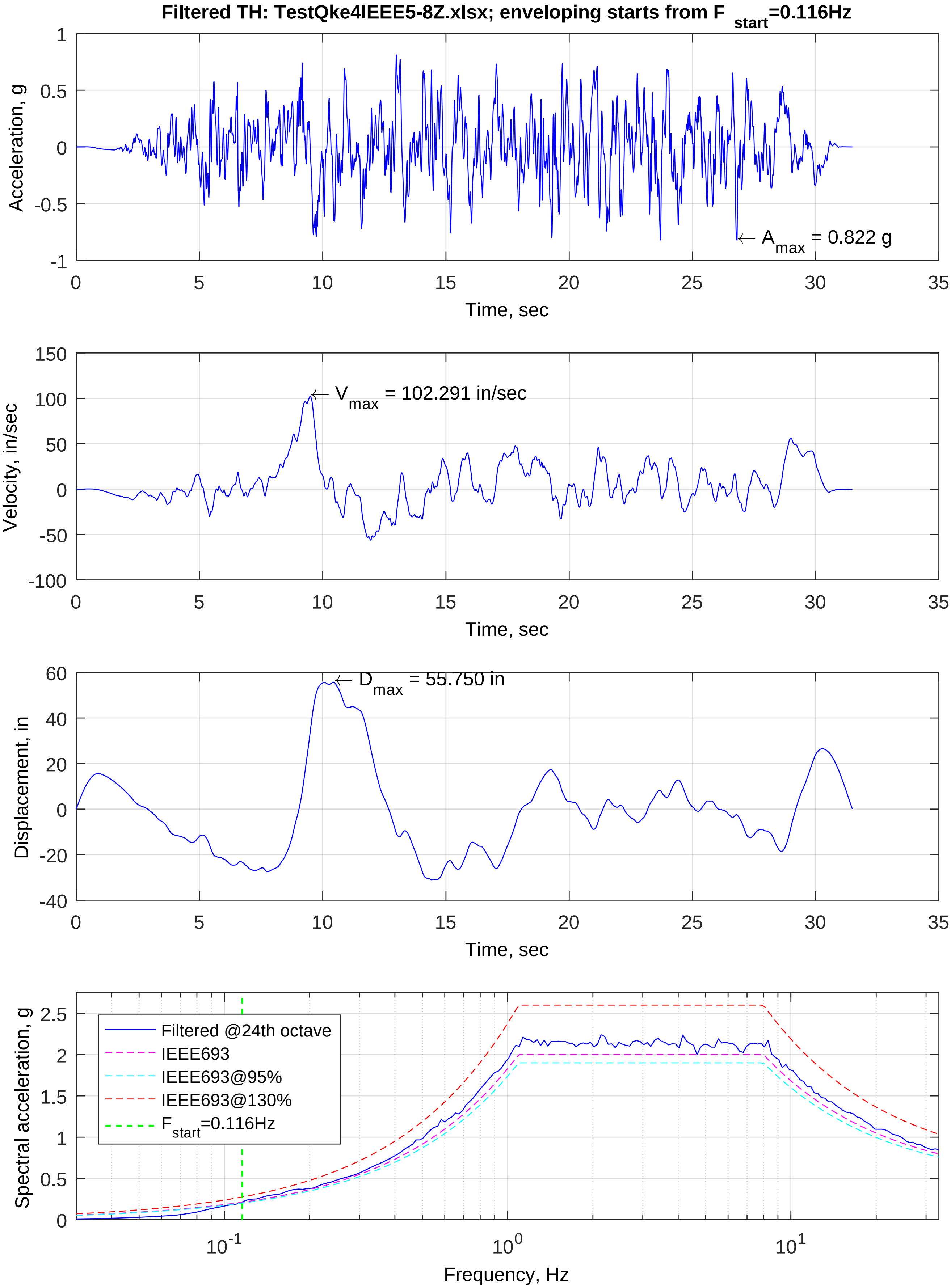

Figure A-24. Summary plots for TestQke4IEEE5-8Z.xlsx

Appendix B: Plots of Filtered Time Histories: Acceleration, Velocity, Displacement and Spectra

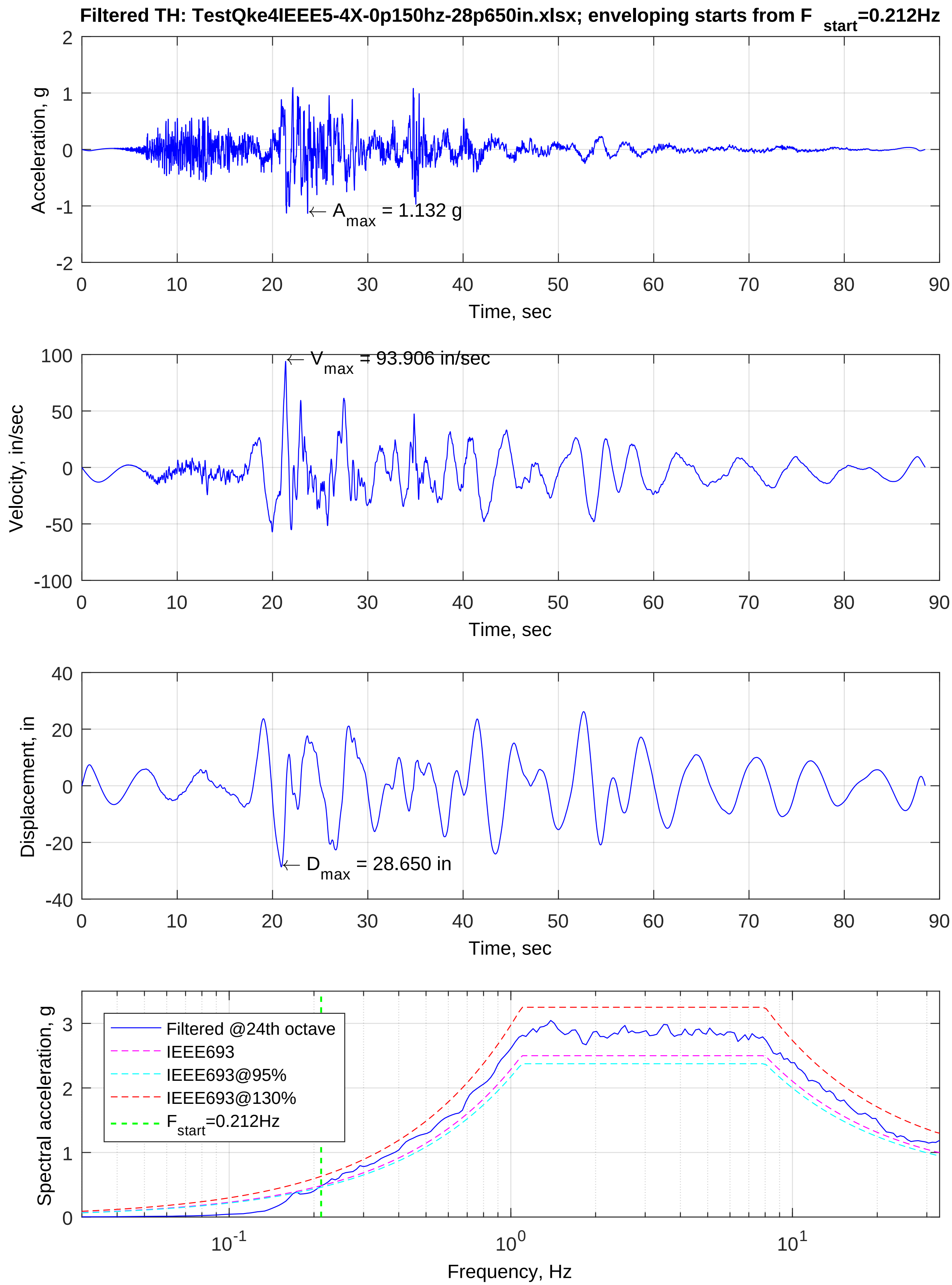

Figure B-1. Summary plots for TestQke4IEEE5-4X-0p150hz-28p650in.xlsx

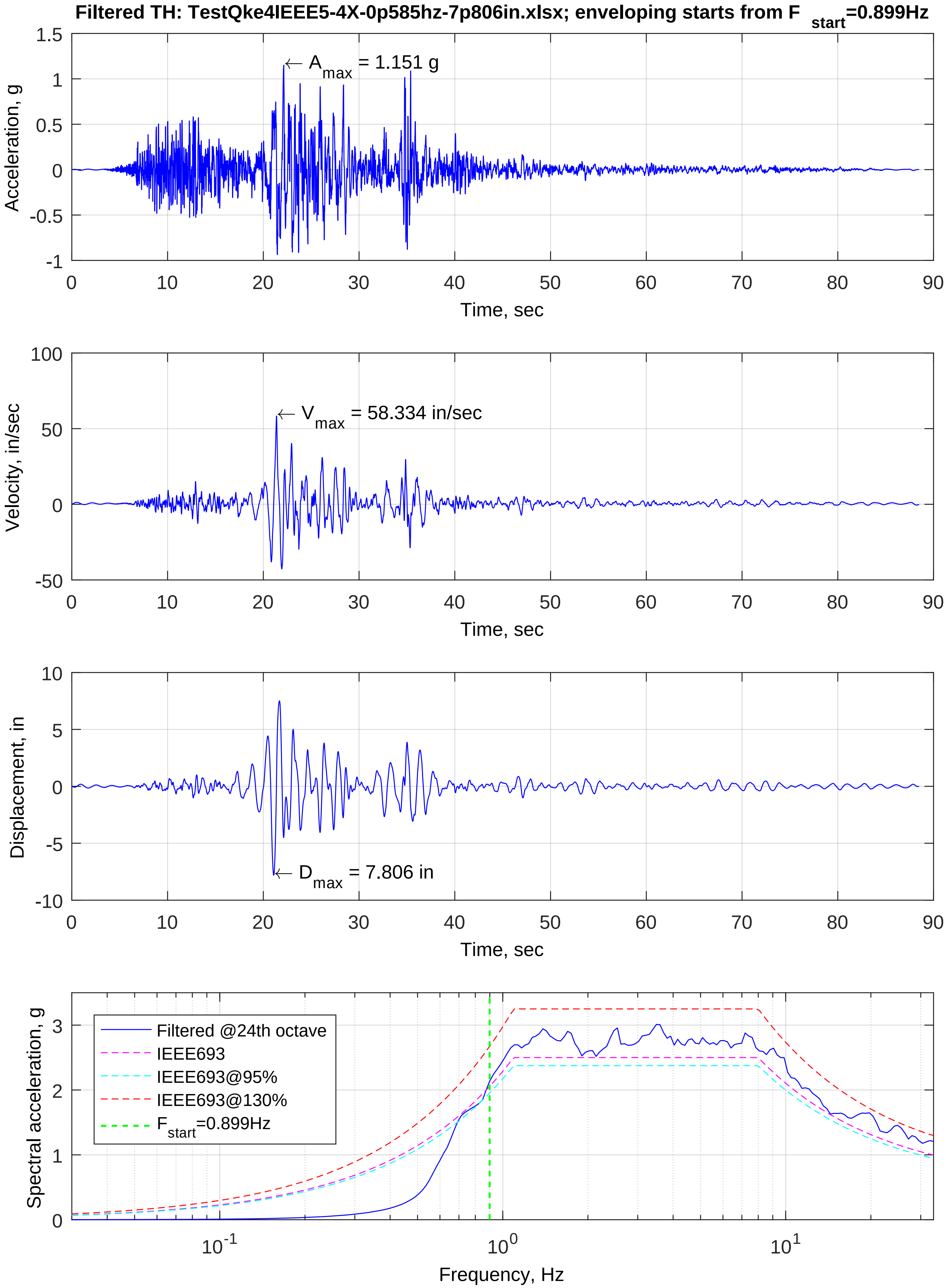

Figure B-2. Summary plots for TestQke4IEEE5-4X-0p585hz-7p806in.xlsx

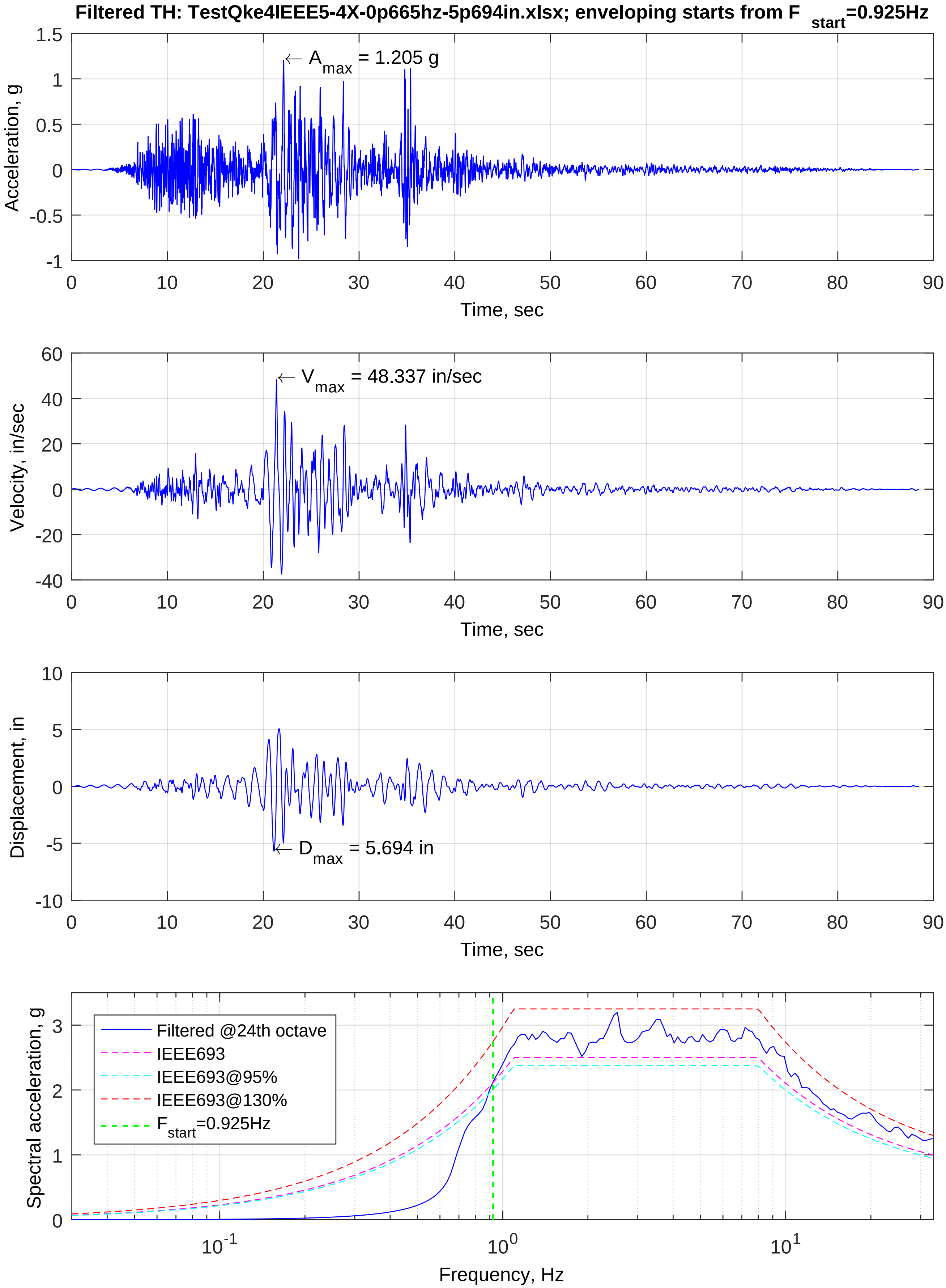

Figure B-3. Summary plots for TestQke4IEEE5-4X-0p665hz-5p694in.xlsx

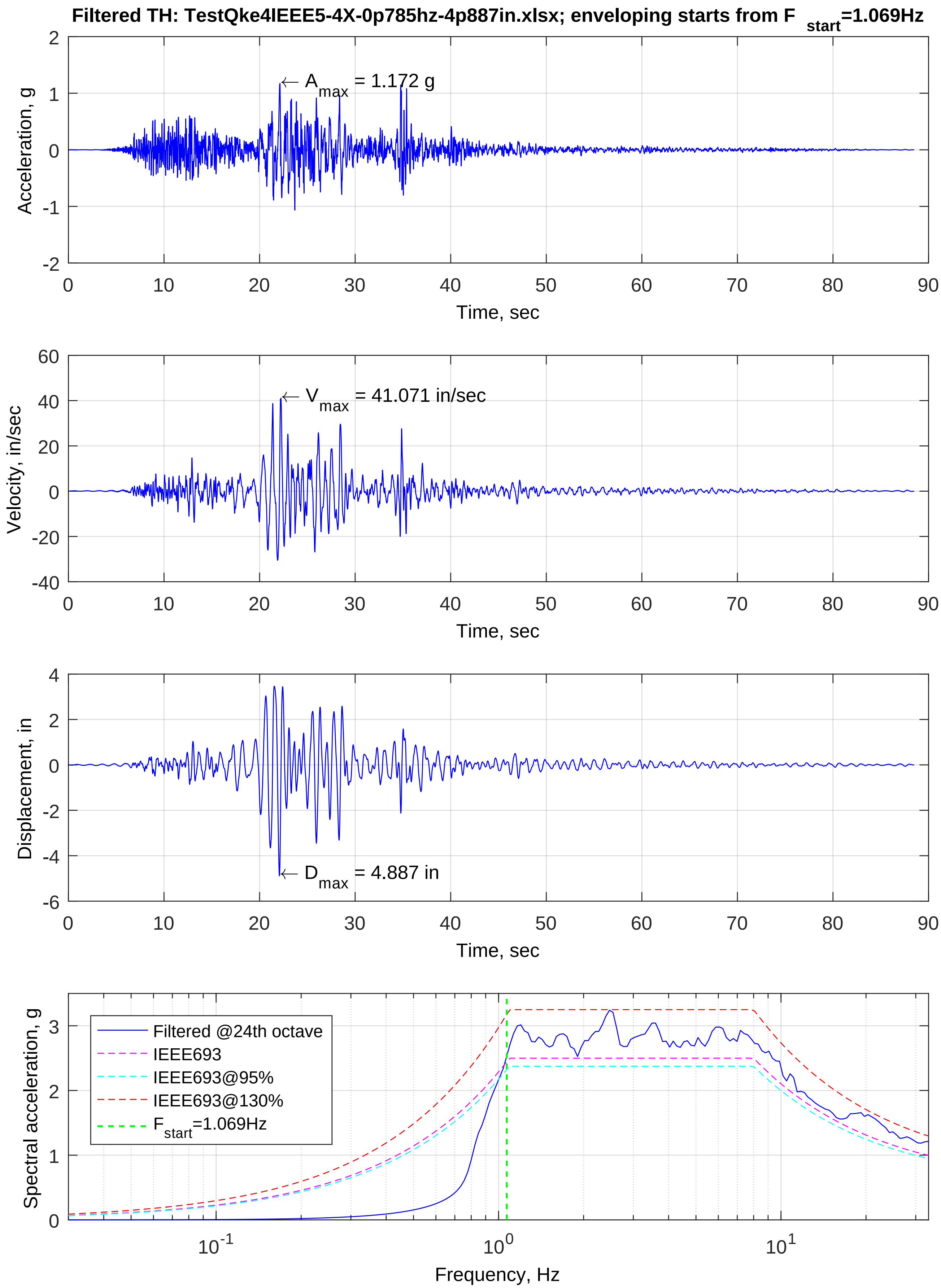

Figure B-4. Summary plots for TestQke4IEEE5-4X-0p785hz-4p887in.xlsx

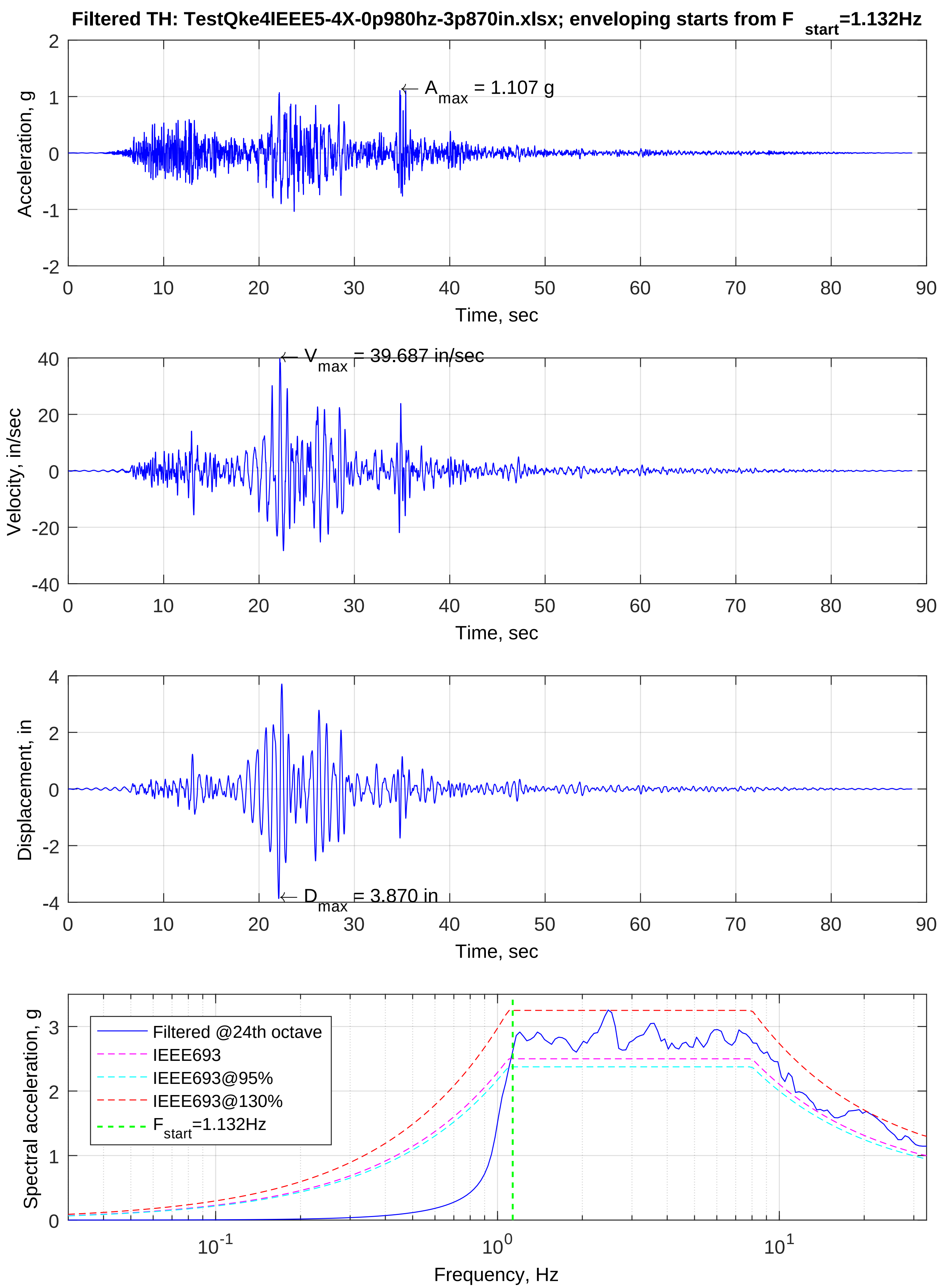

Figure B-5. Summary plots for TestQke4IEEE5-4X-0p980hz-3p870in.xlsx

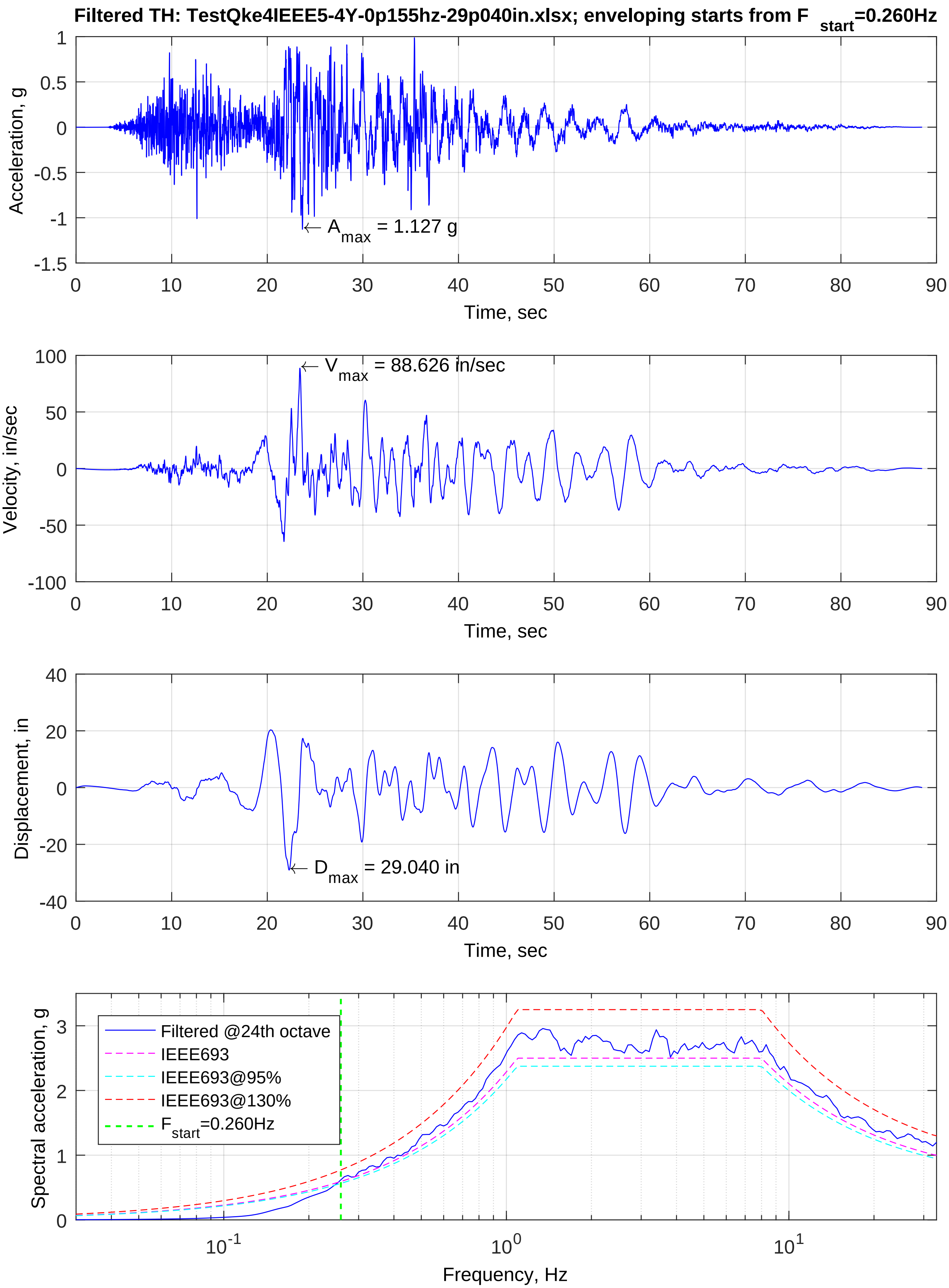

Figure B-6. Summary plots for TestQke4IEEE5-4Y-0p155hz-29p040in.xlsx

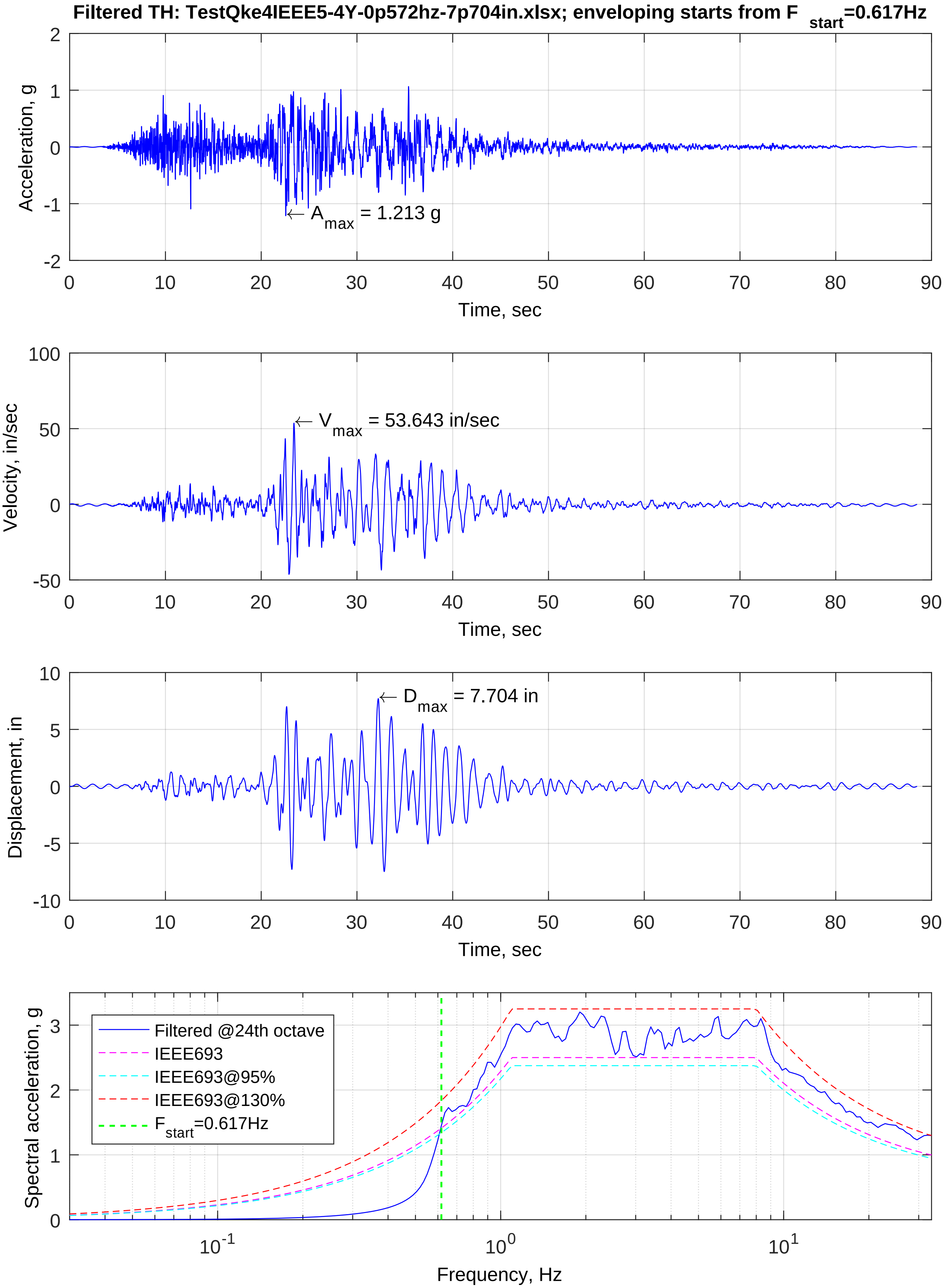

Figure B-7. Summary plots for TestQke4IEEE5-4Y-0p572hz-7p704in.xlsx

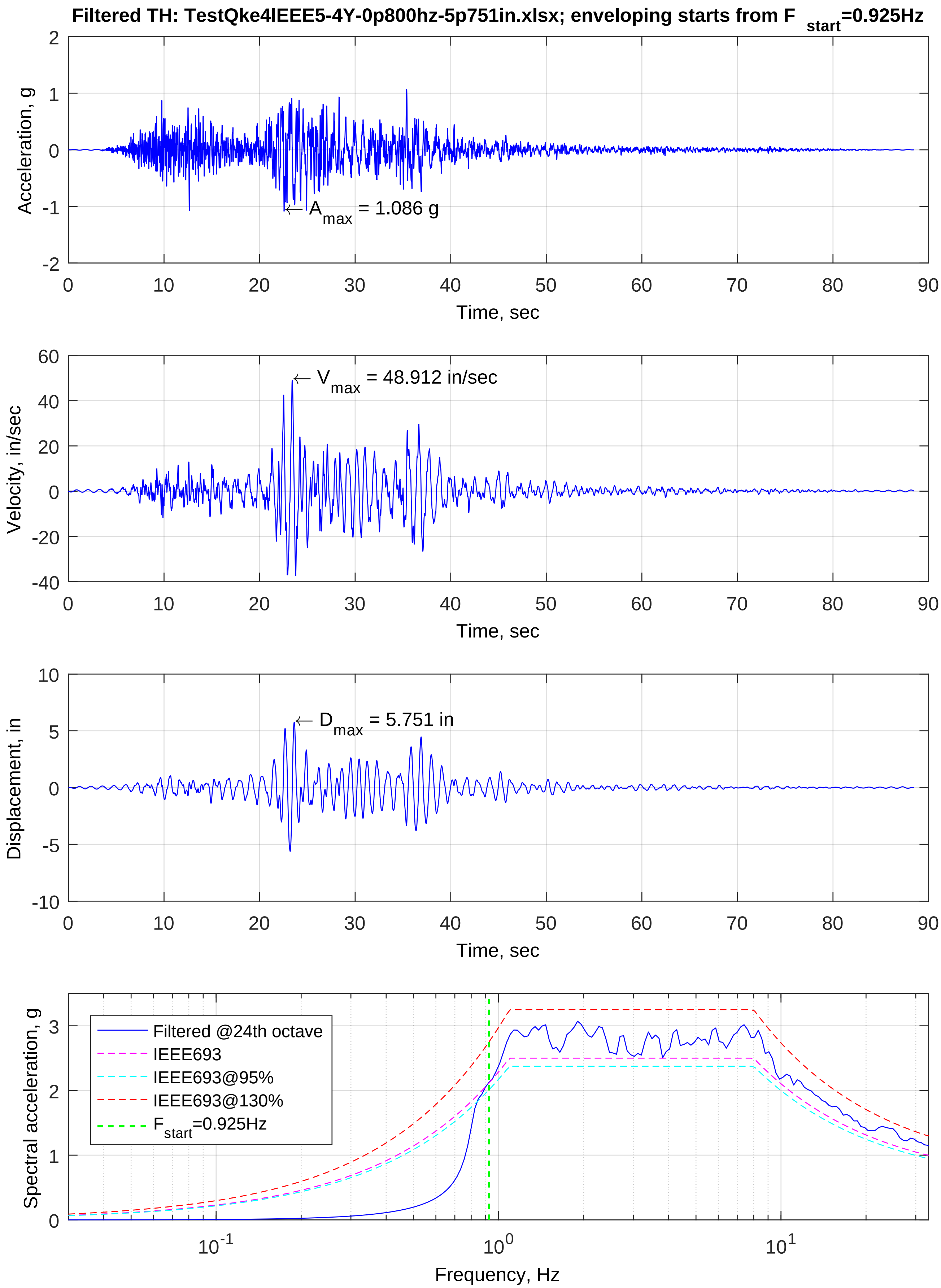

Figure B-8. Summary plots for TestQke4IEEE5-4Y-0p800hz-5p751in.xlsx

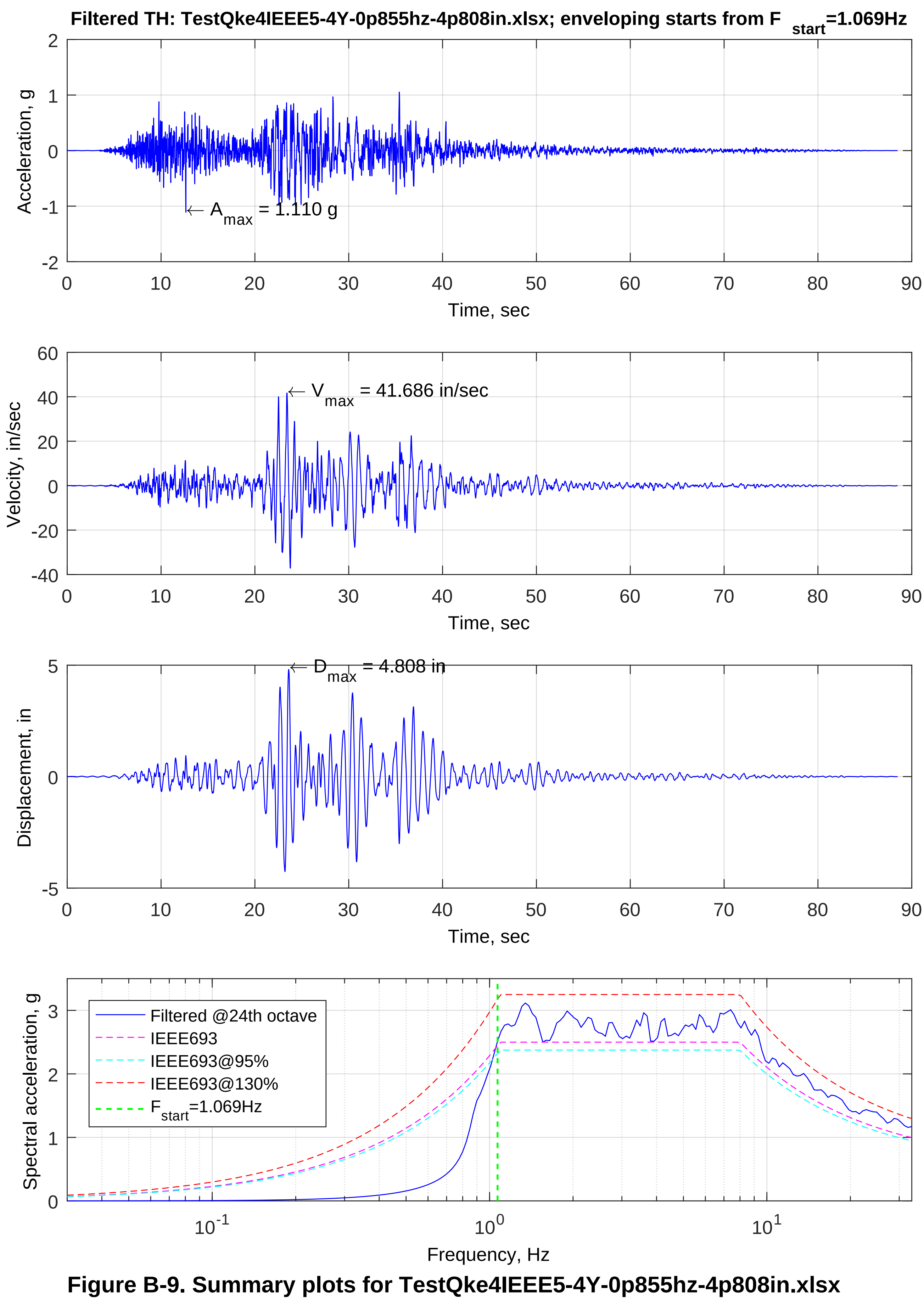

Figure B-9. Summary plots for TestQke4IEEE5-4Y-0p855hz-4p808in.xlsx

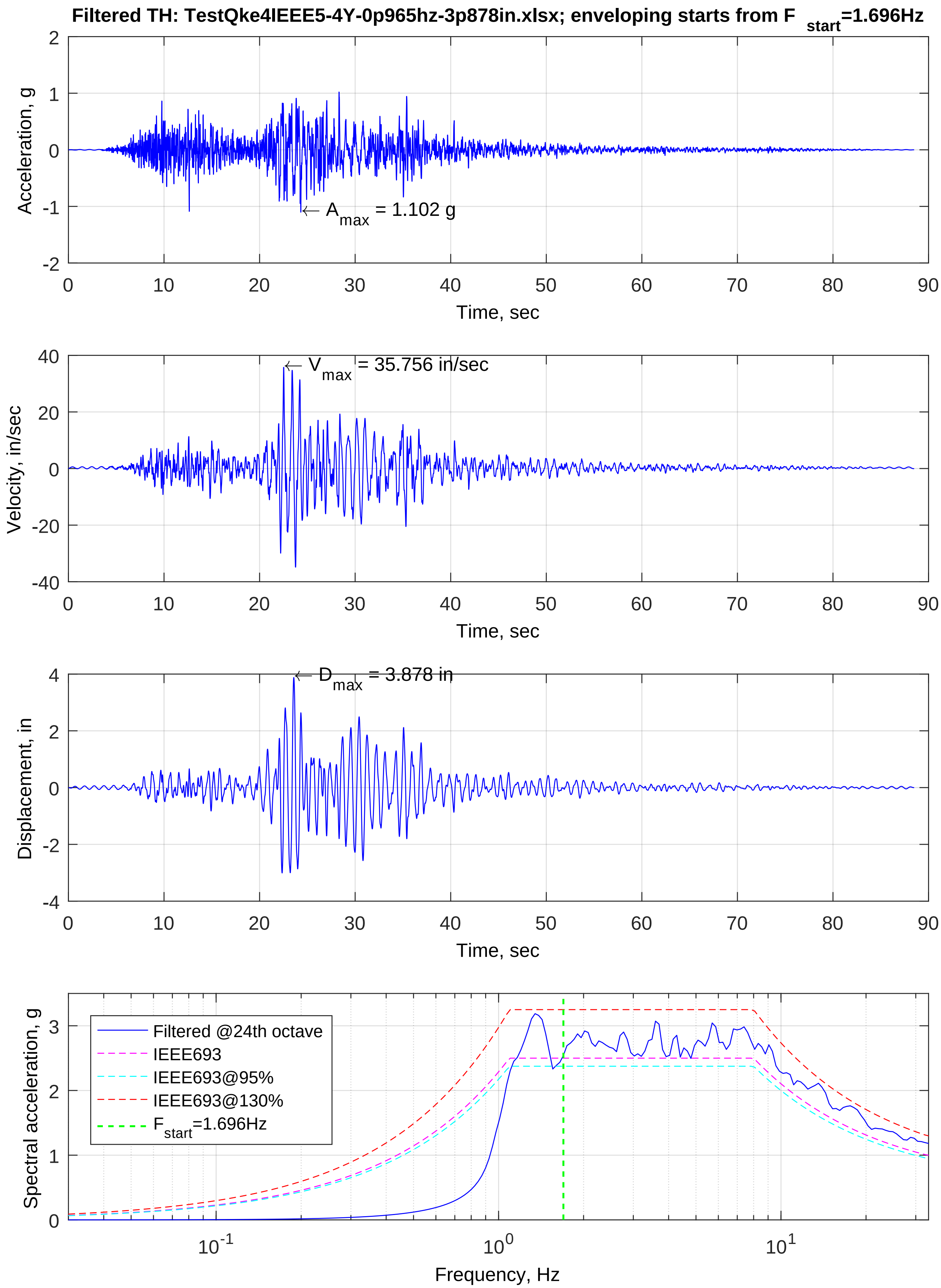

Figure B-10. Summary plots for TestQke4IEEE5-4Y-0p965hz-3p878in.xlsx

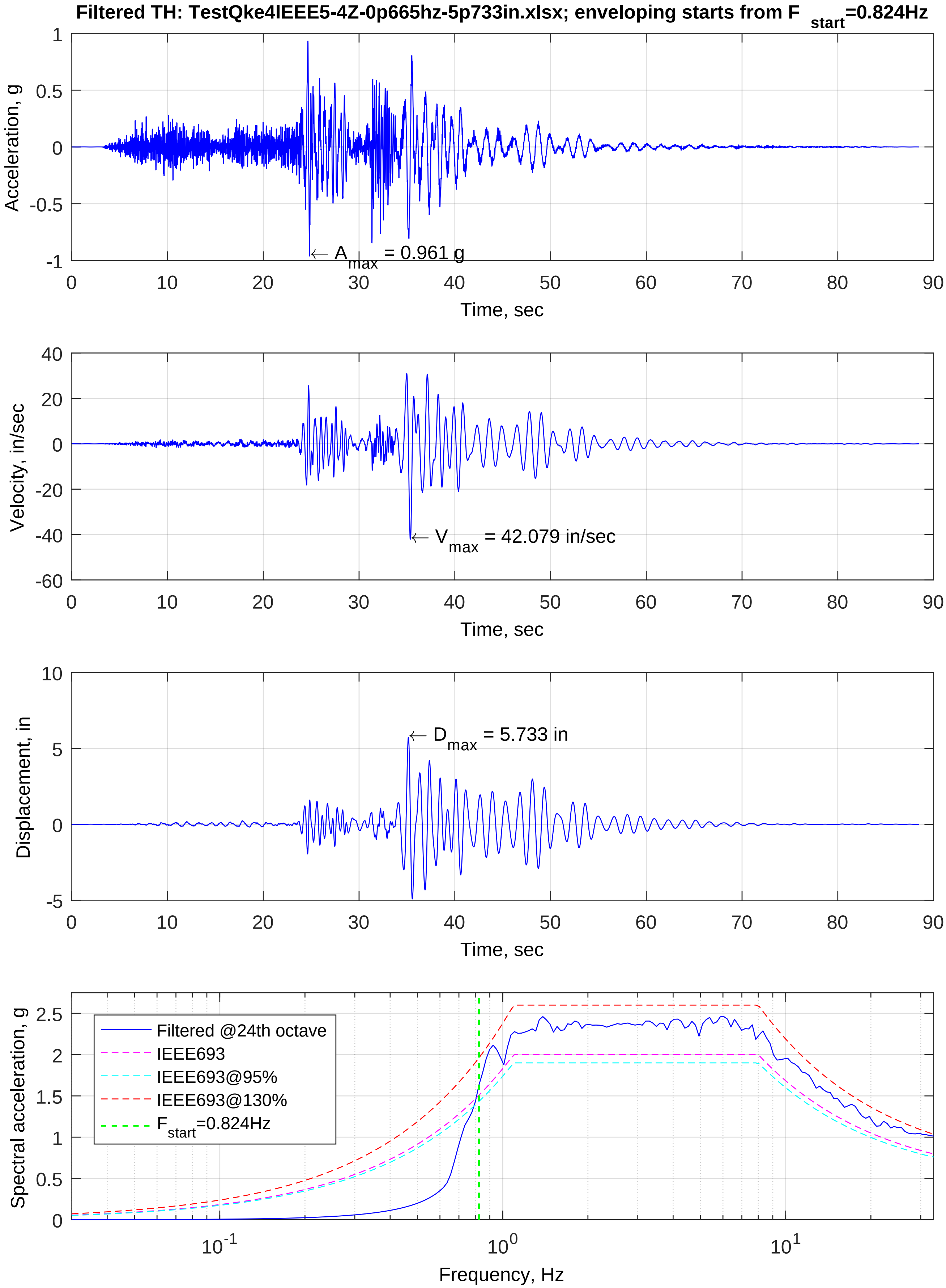

Figure B-11. Summary plots for TestQke4IEEE5-4Z-0p665hz-5p733in.xlsx

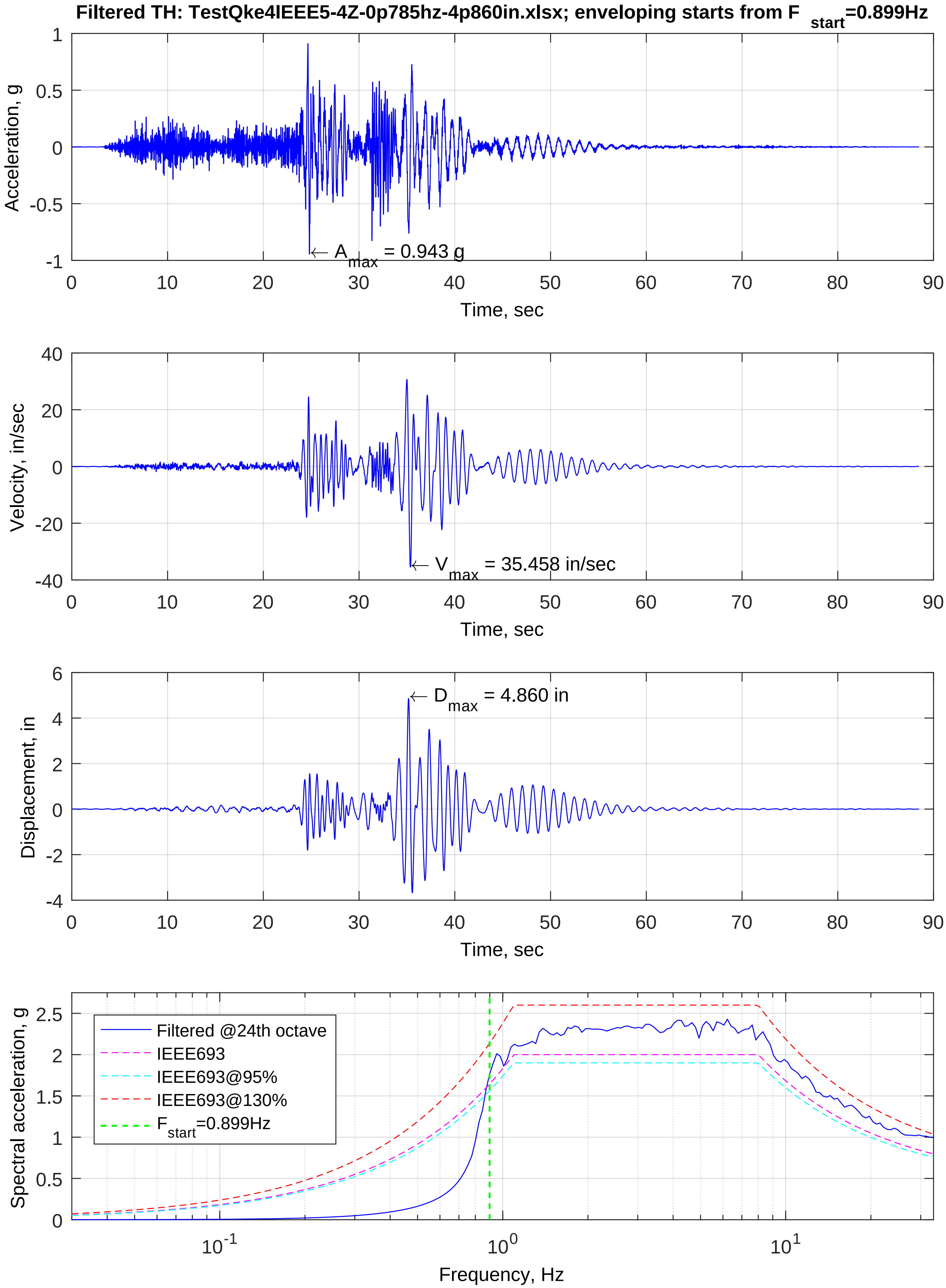

Figure B-12. Summary plots for TestQke4IEEE5-4Z-0p785hz-4p860in.xlsx

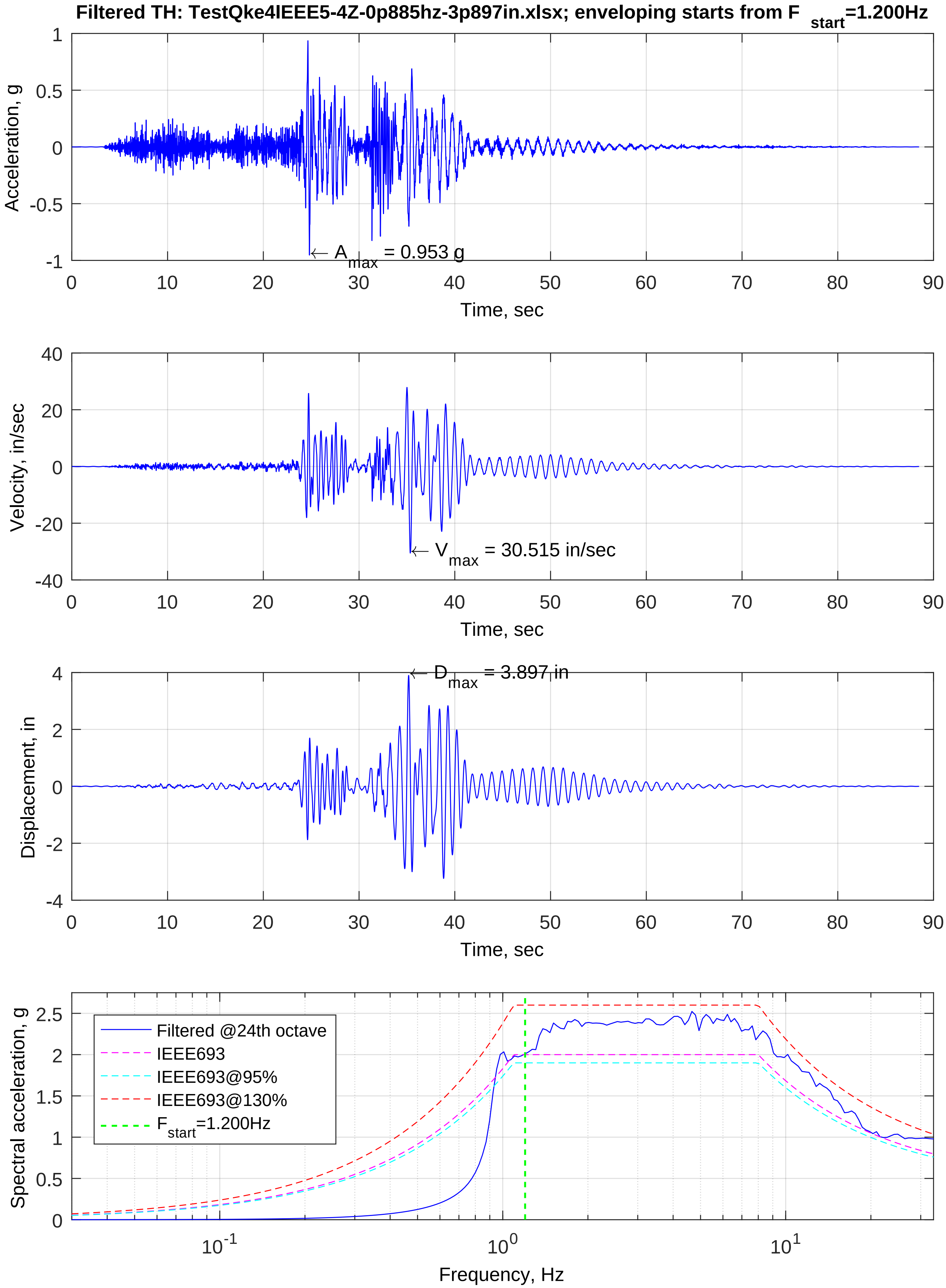

Figure B-13. Summary plots for TestQke4IEEE5-4Z-0p885hz-3p897in.xlsx

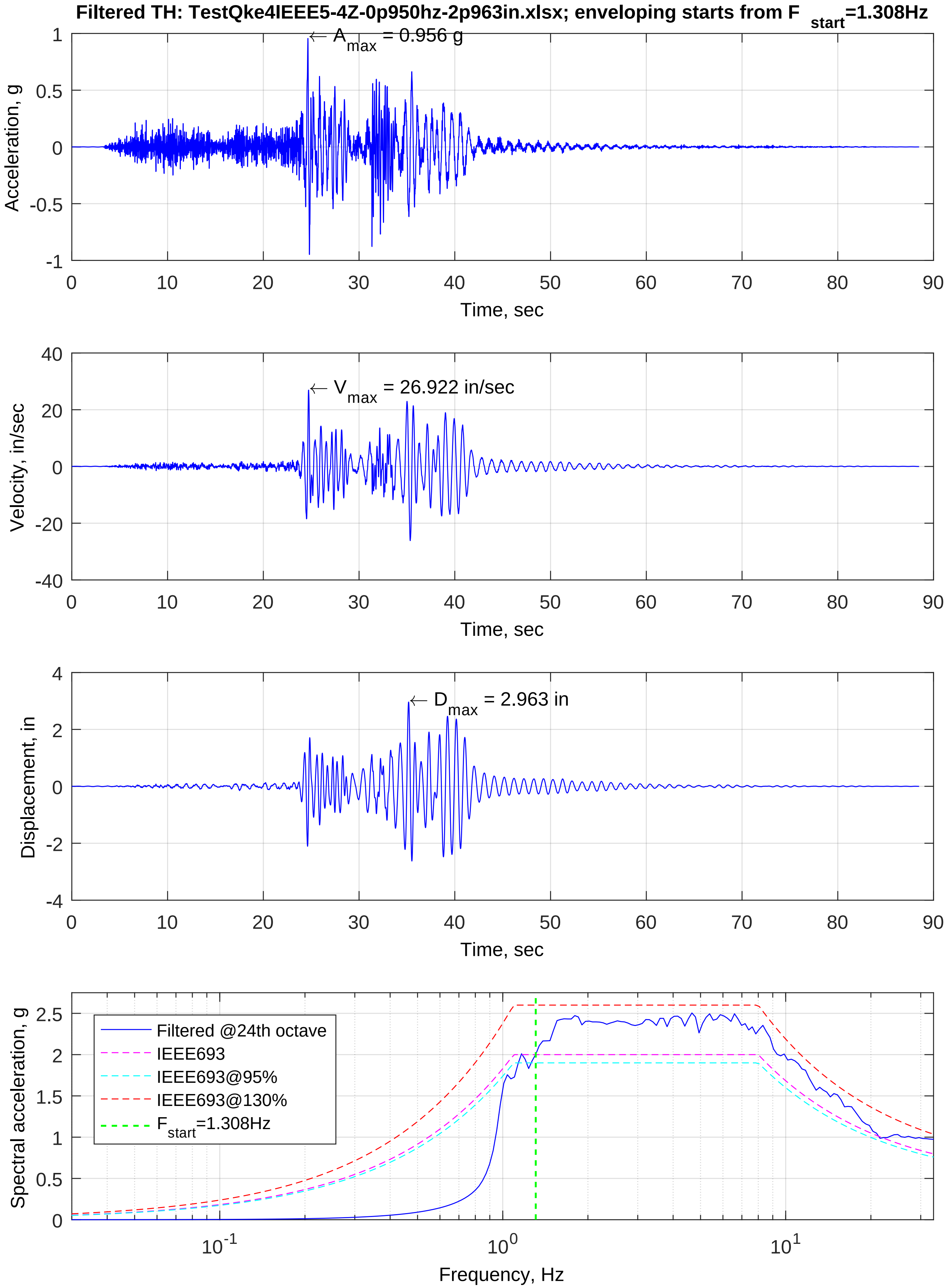

Figure B-14. Summary plots for TestQke4IEEE5-4Z-0p950hz-2p963in.xlsx

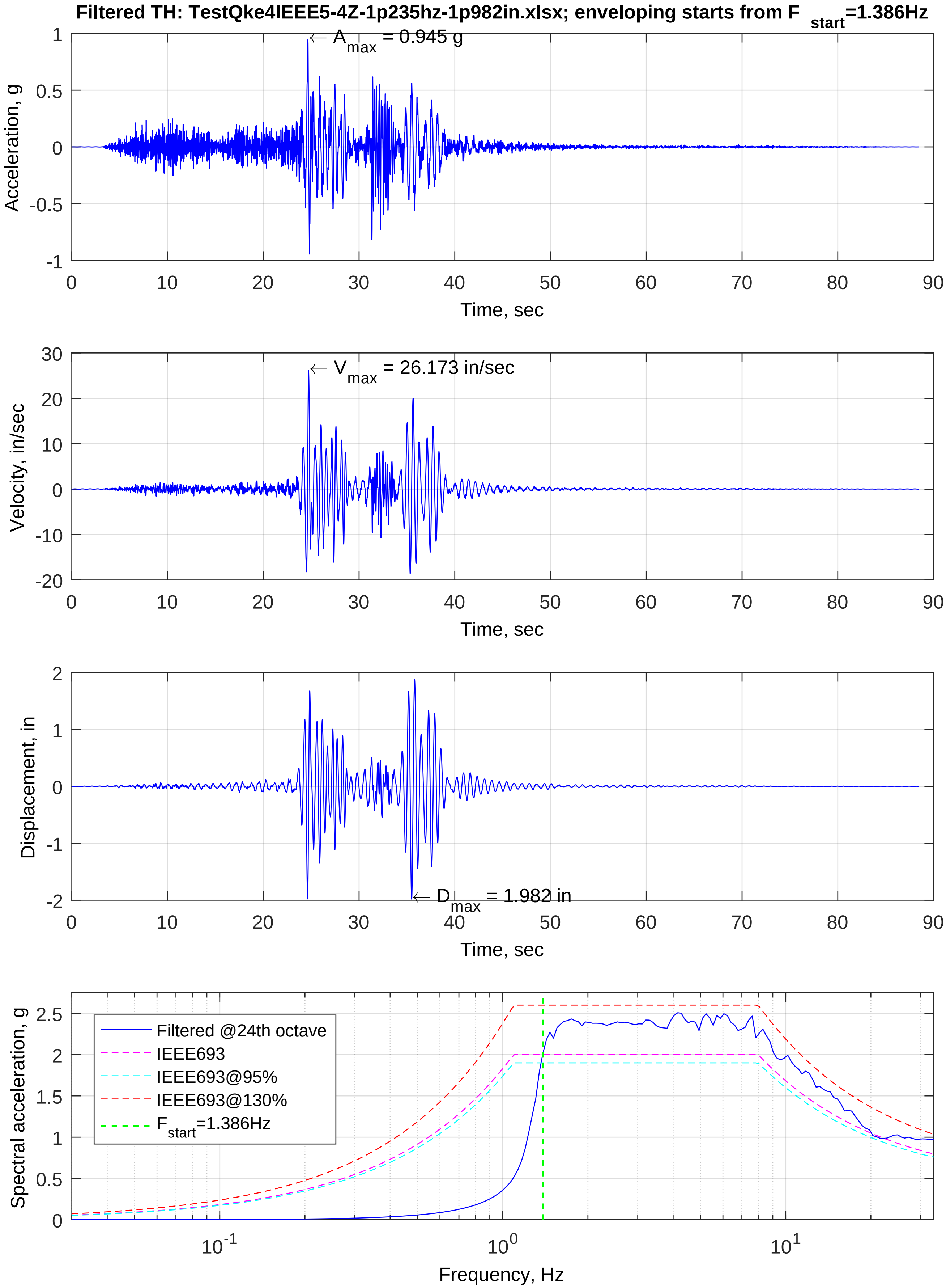

Figure B-15. Summary plots for TestQke4IEEE5-4Z-1p235hz-1p982in.xlsx

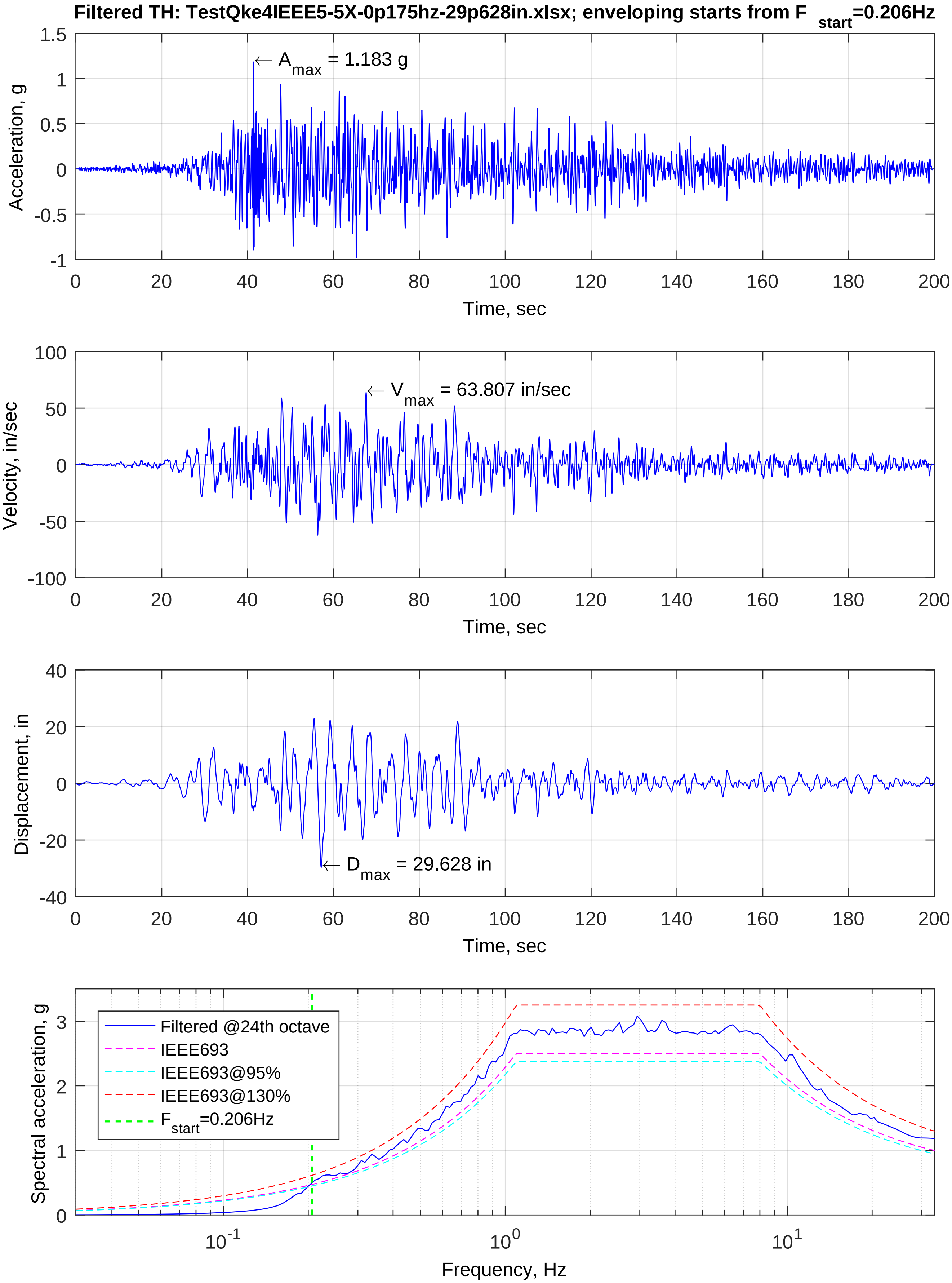

Figure B-16. Summary plots for TestQke4IEEE5-5X-0p175hz-29p628in.xlsx

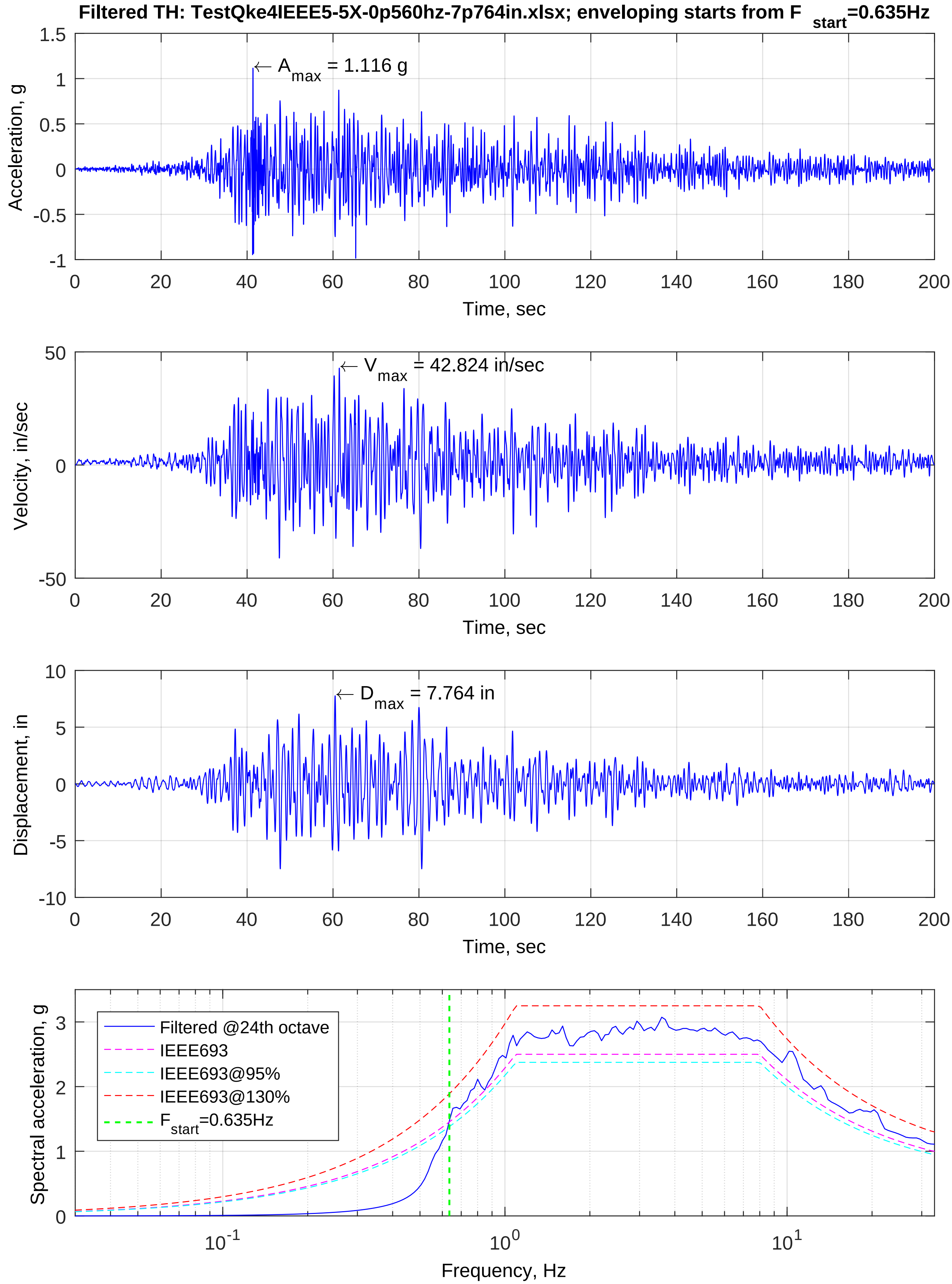

Figure B-17. Summary plots for TestQke4IEEE5-5X-0p560hz-7p764in.xlsx

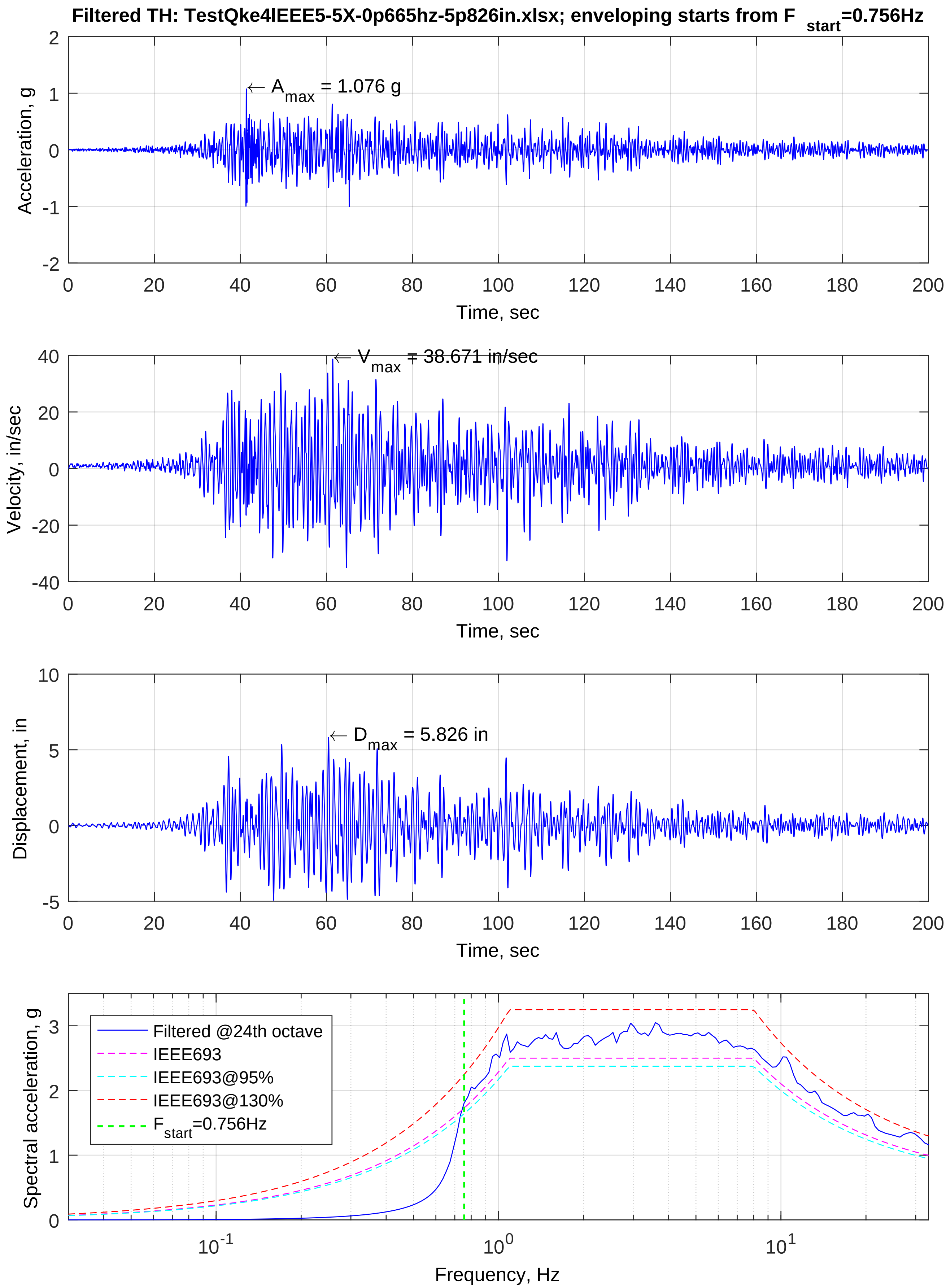

Figure B-18. Summary plots for TestQke4IEEE5-5X-0p665hz-5p826in.xlsx

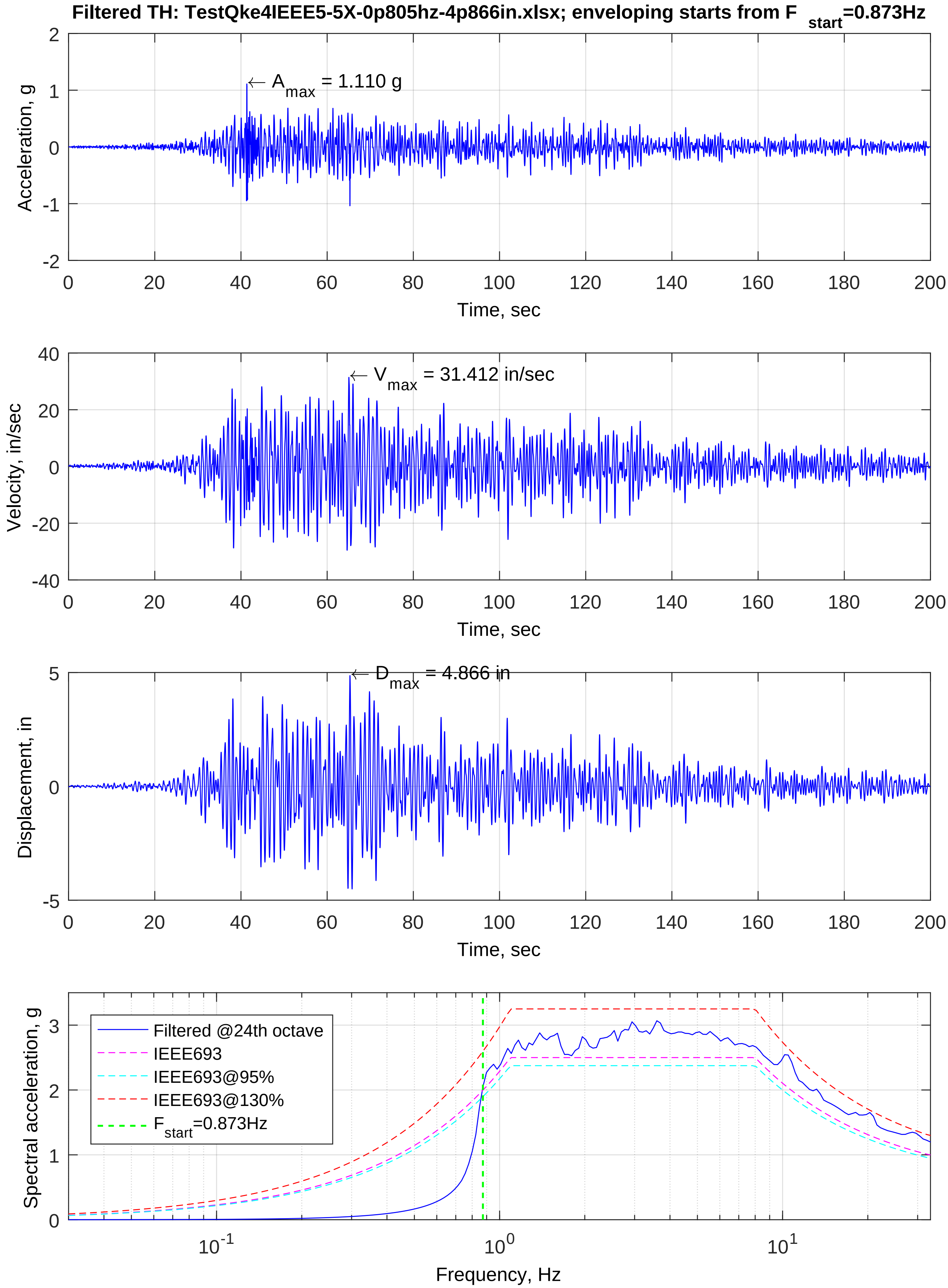

Figure B-19. Summary plots for TestQke4IEEE5-5X-0p805hz-4p866in.xlsx

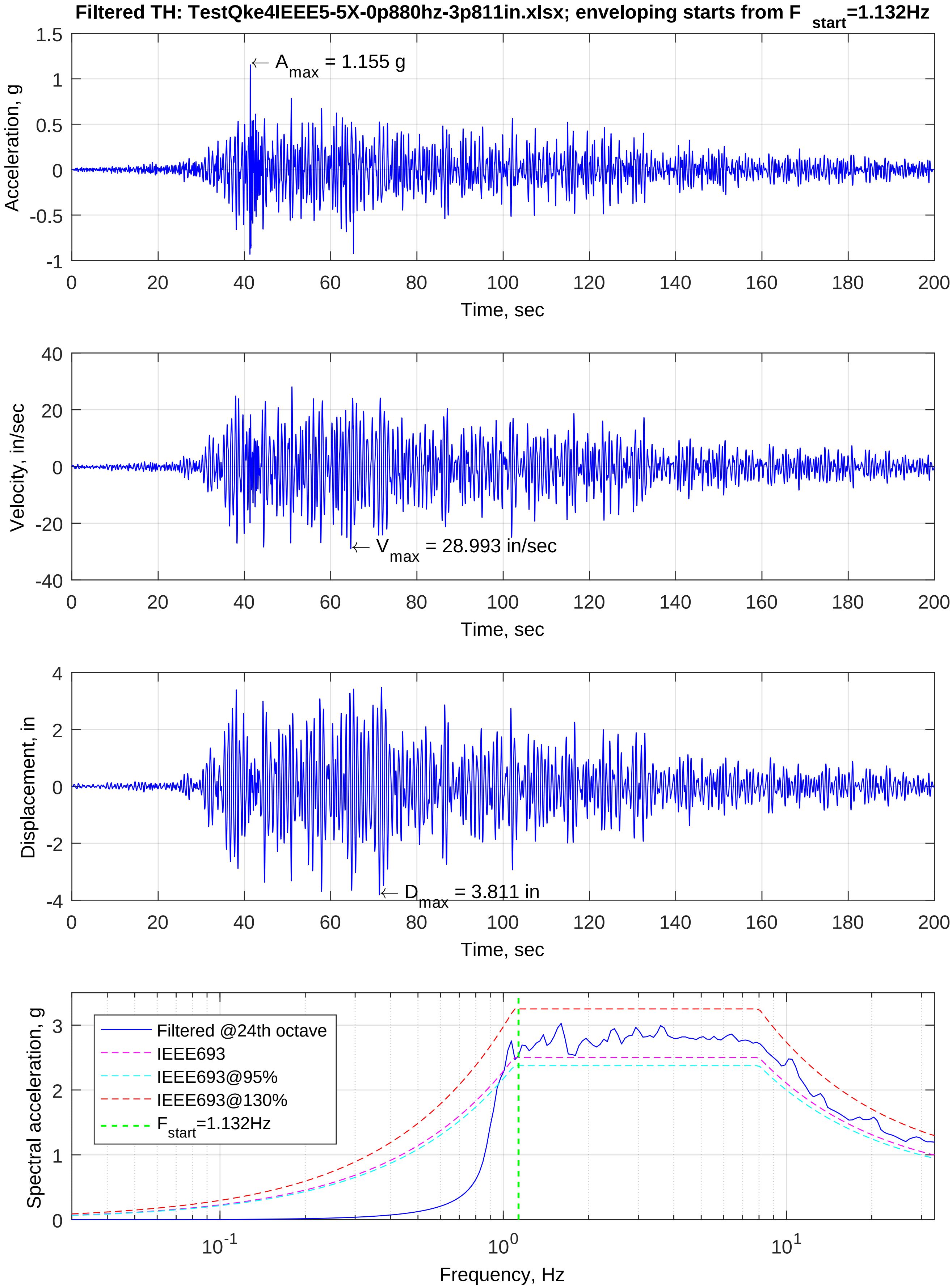

Figure B-20. Summary plots for TestQke4IEEE5-5X-0p880hz-3p811in.xlsx

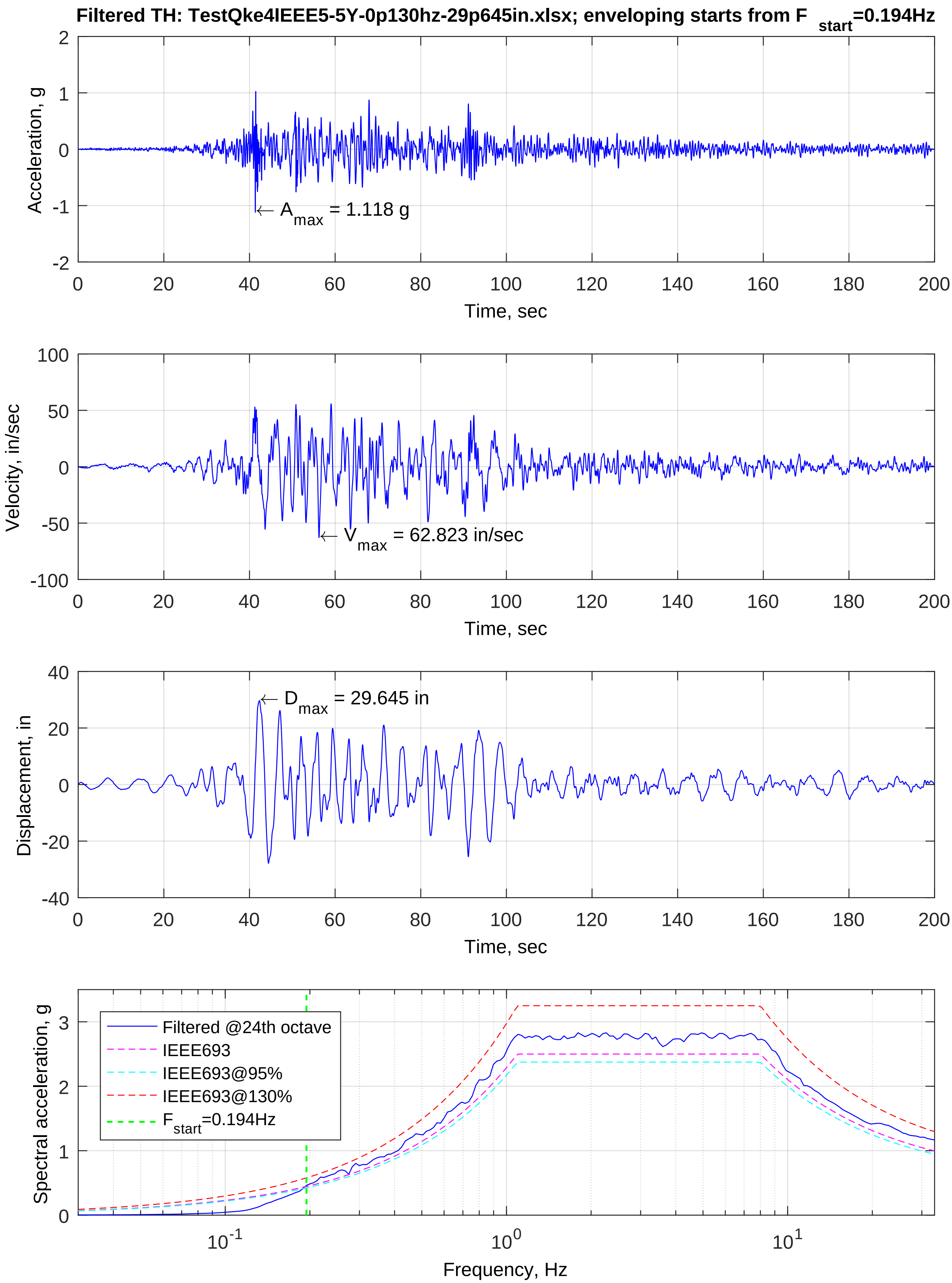

Figure B-21. Summary plots for TestQke4IEEE5-5Y-0p130hz-29p645in.xlsx

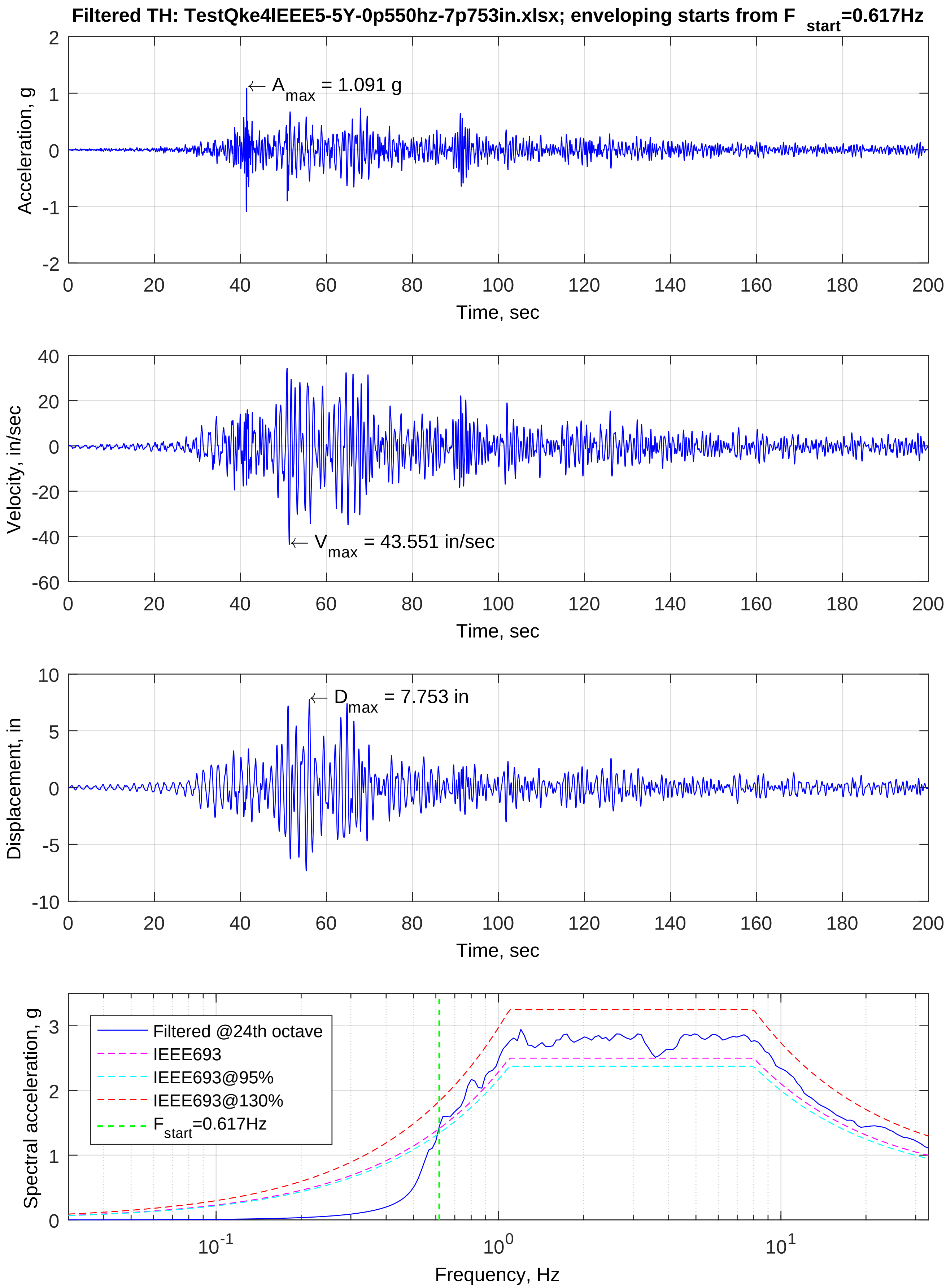

Figure B-22. Summary plots for TestQke4IEEE5-5Y-0p550hz-7p753in.xlsx

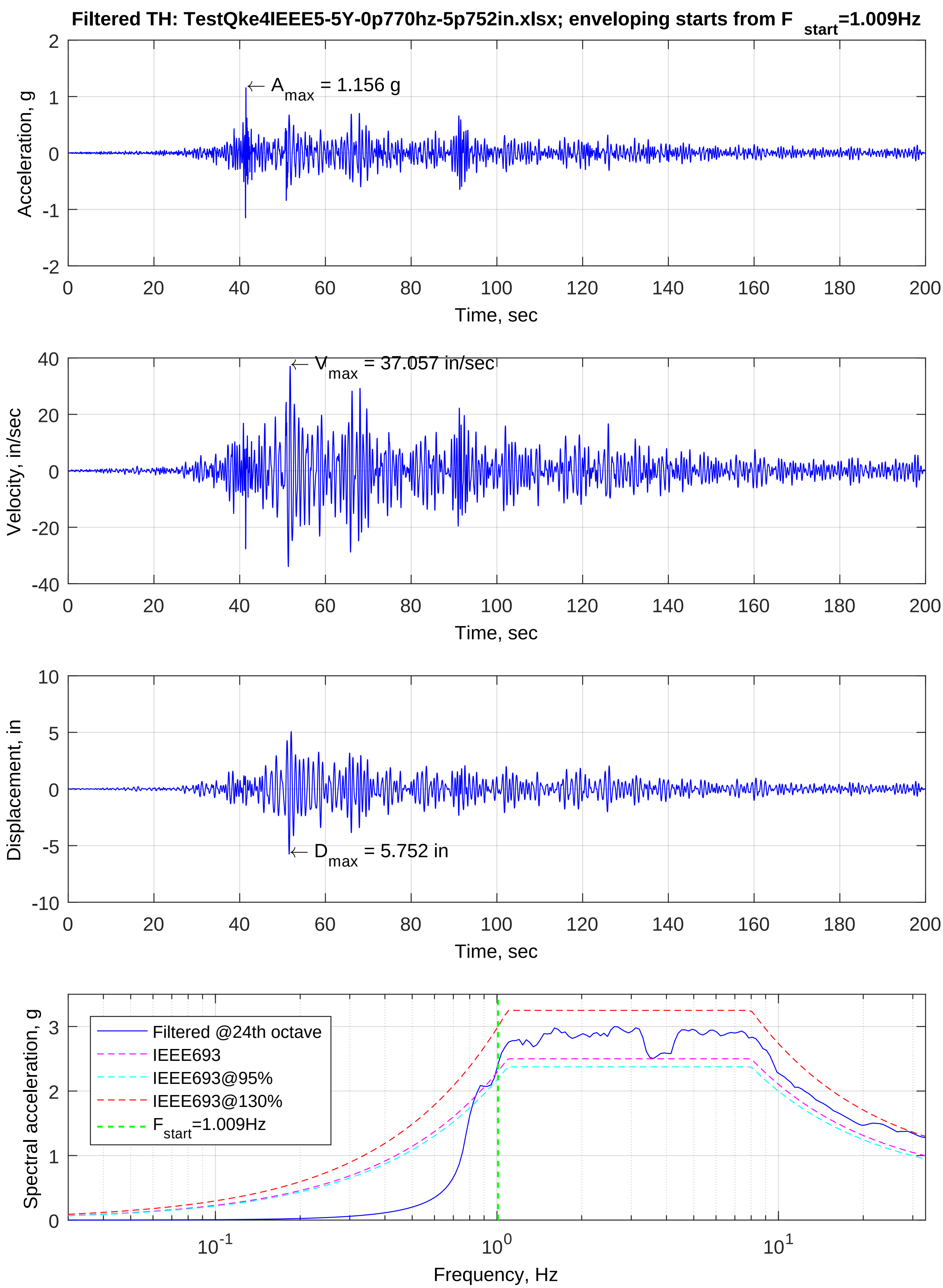

Figure B-23. Summary plots for TestQke4IEEE5-5Y-0p770hz-5p752in.xlsx

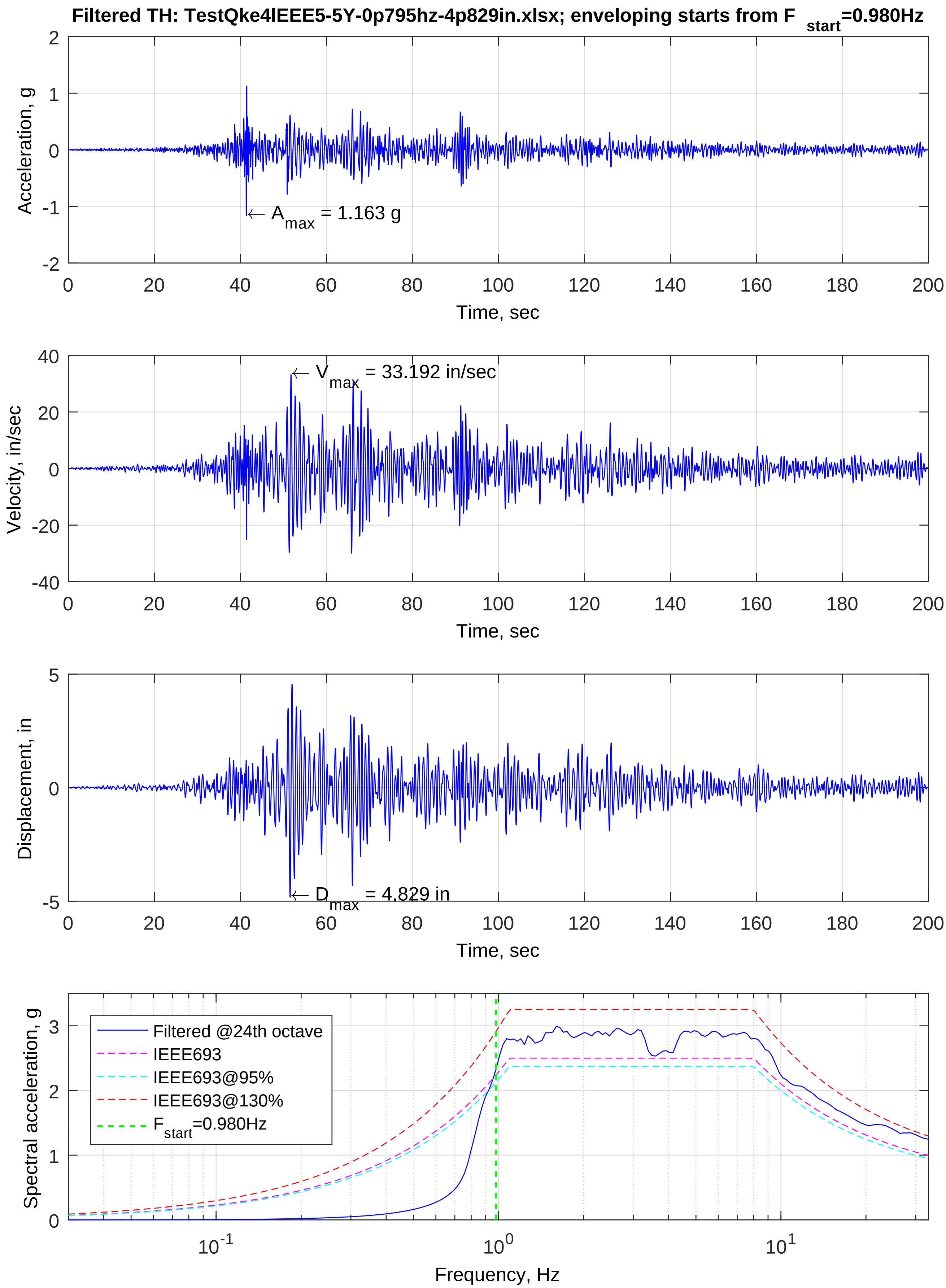

Figure B-24. Summary plots for TestQke4IEEE5-5Y-0p795hz-4p829in.xlsx

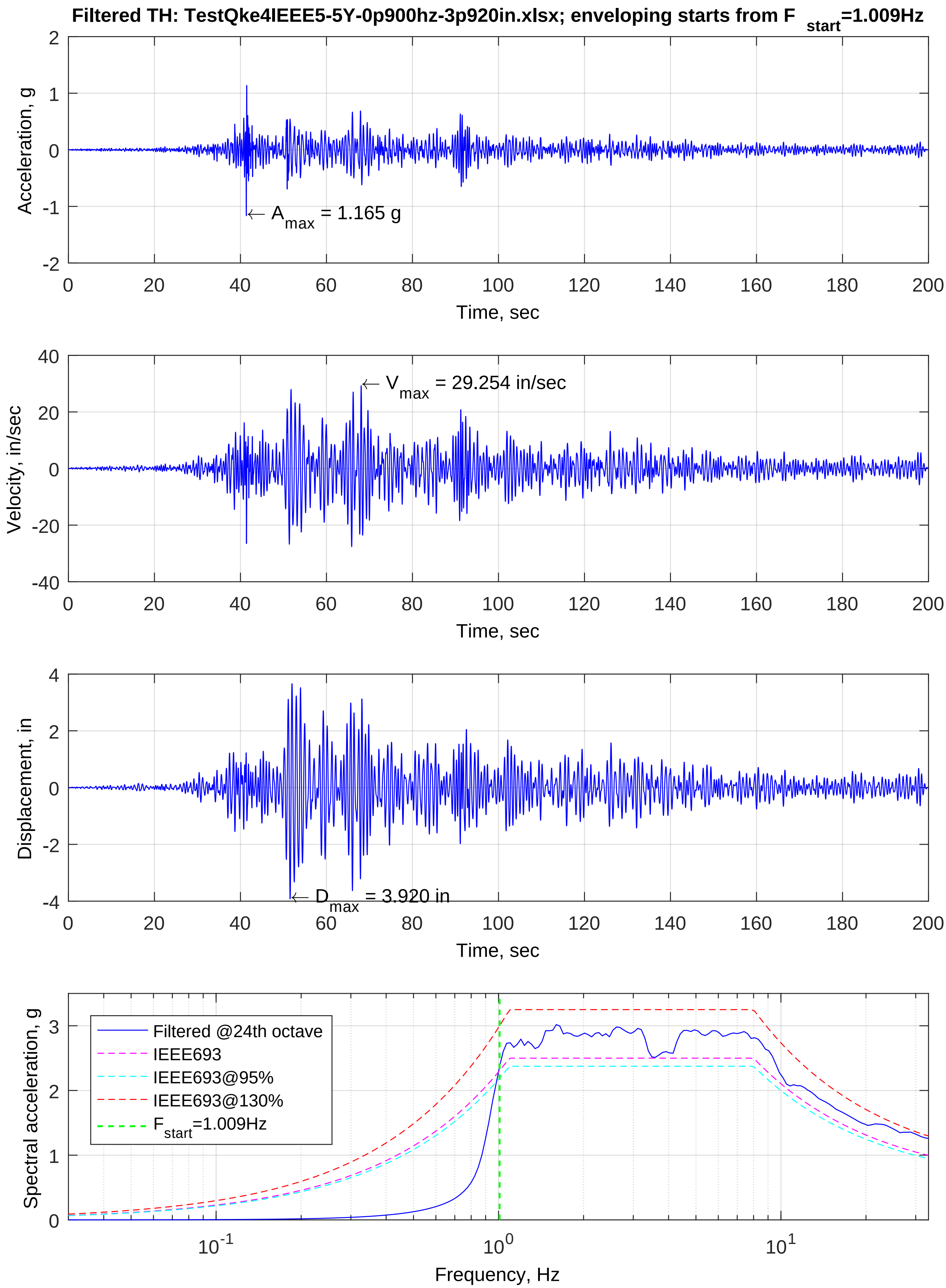

Figure B-25. Summary plots for TestQke4IEEE5-5Y-0p900hz-3p920in.xlsx

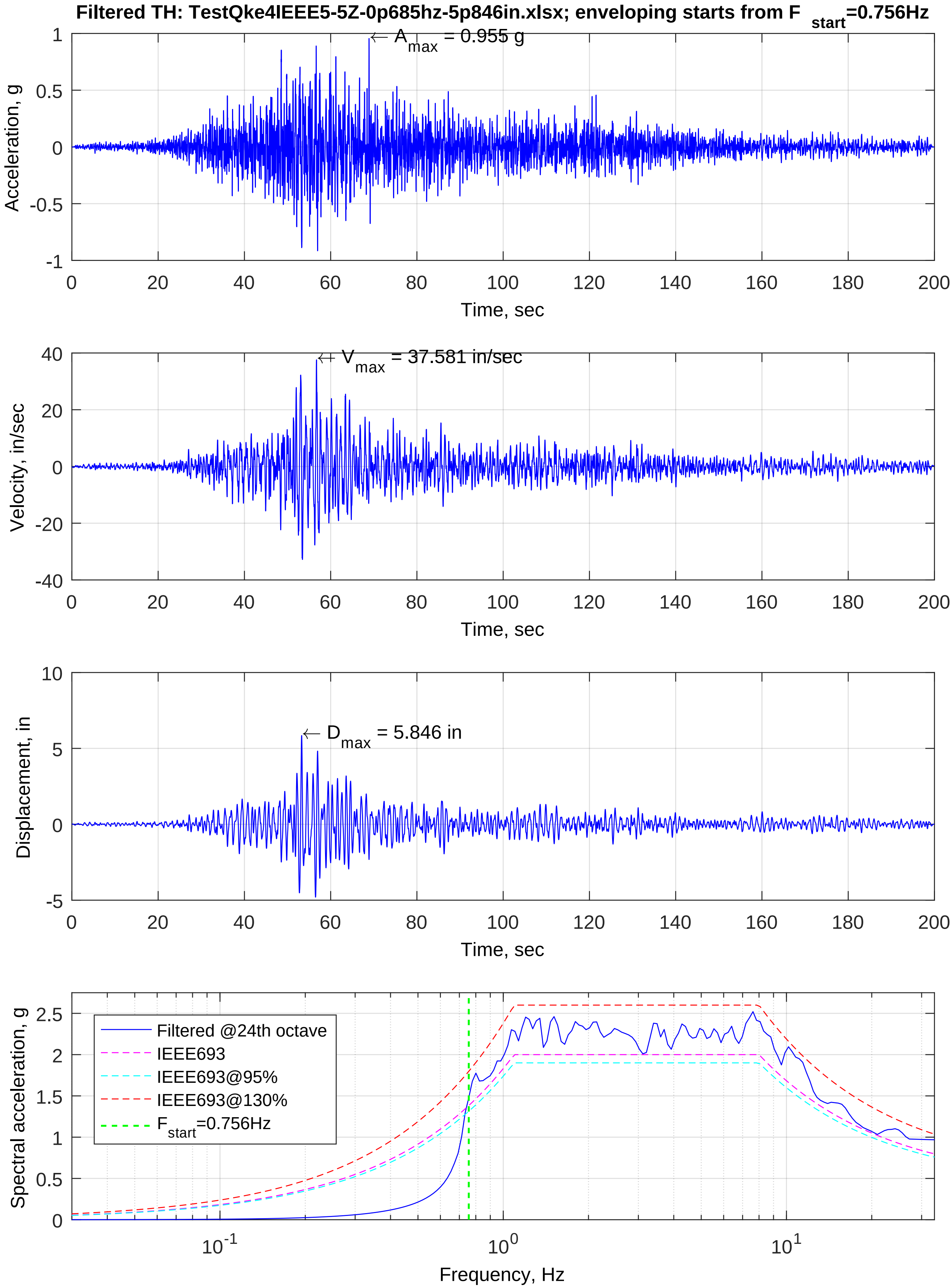

Figure B-26. Summary plots for TestQke4IEEE5-5Z-0p685hz-5p846in.xlsx

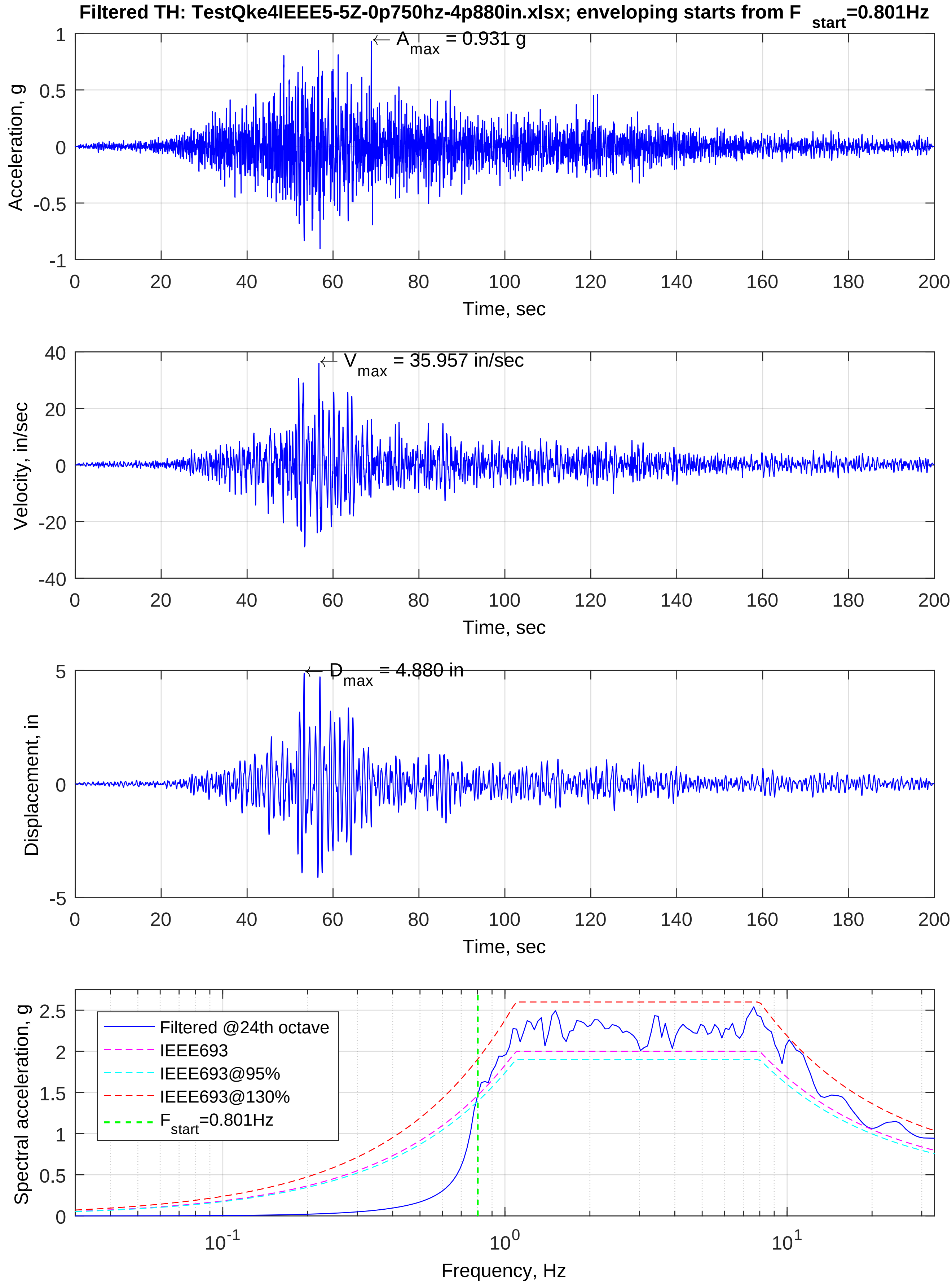

Figure B-27. Summary plots for TestQke4IEEE5-5Z-0p750hz-4p880in.xlsx

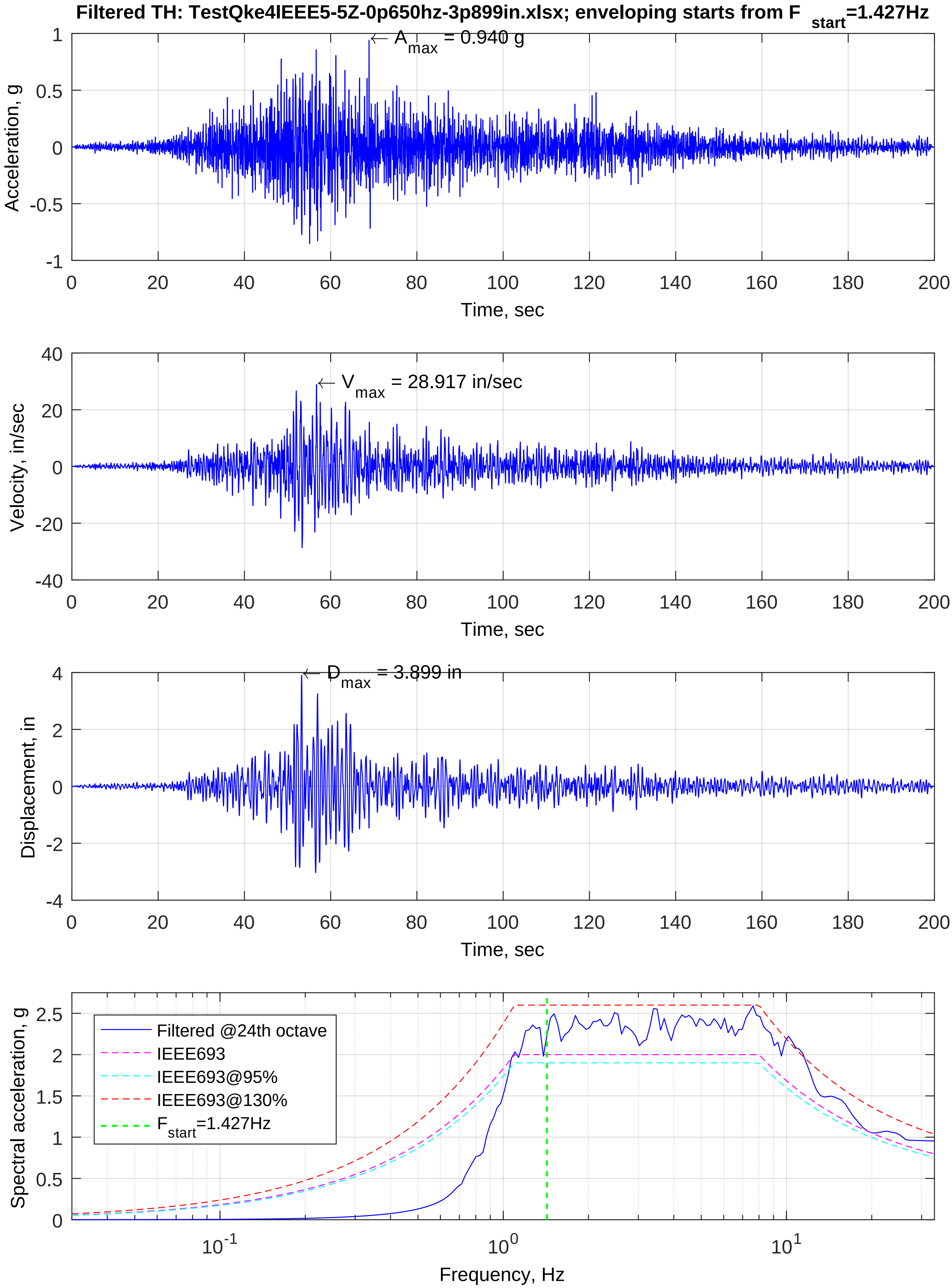

Figure B-28. Summary plots for TestQke4IEEE5-5Z-0p650hz-3p899in.xlsx

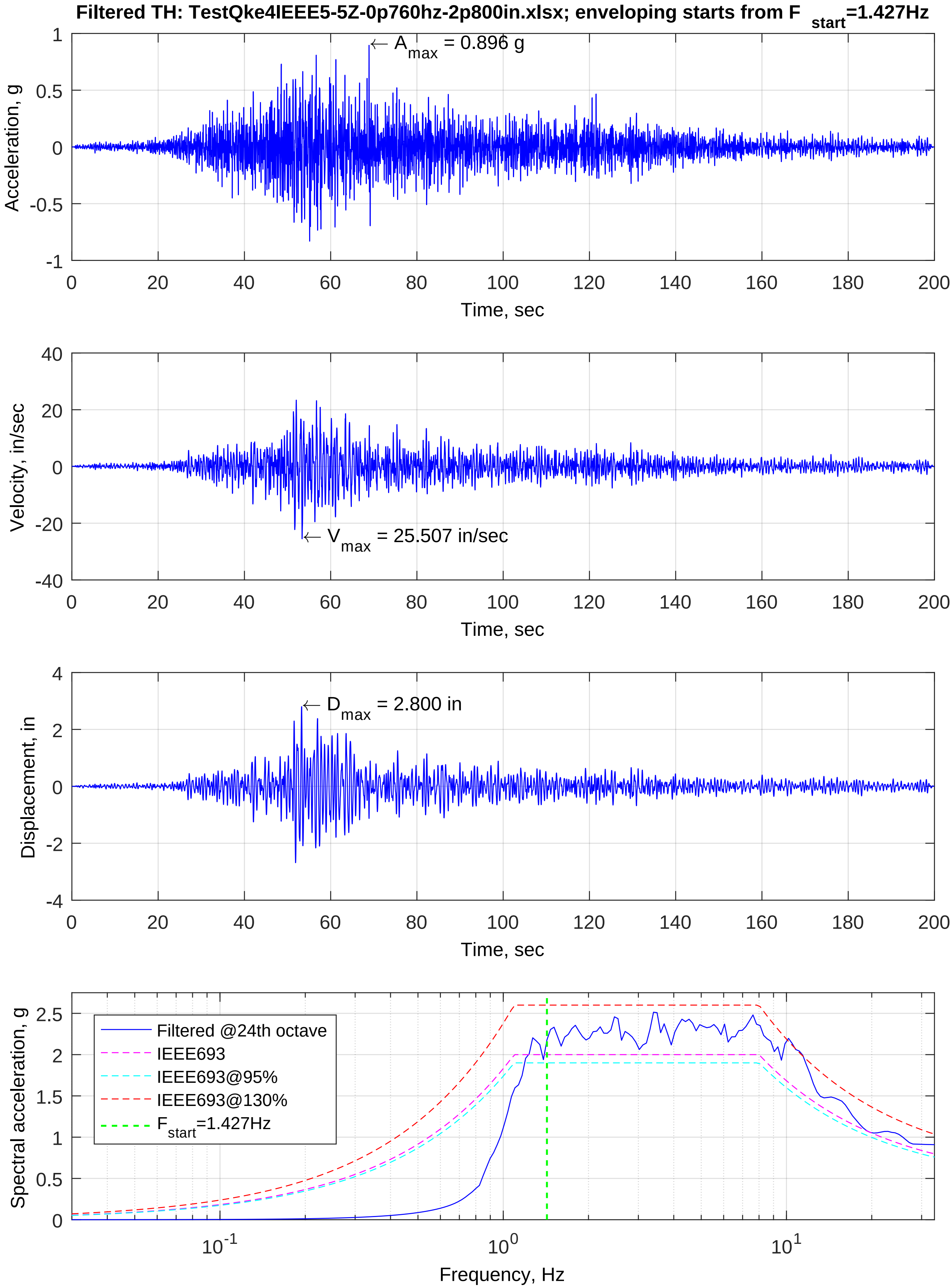

Figure B-29. Summary plots for TestQke4IEEE5-5Z-0p760hz-2p800in.xlsx

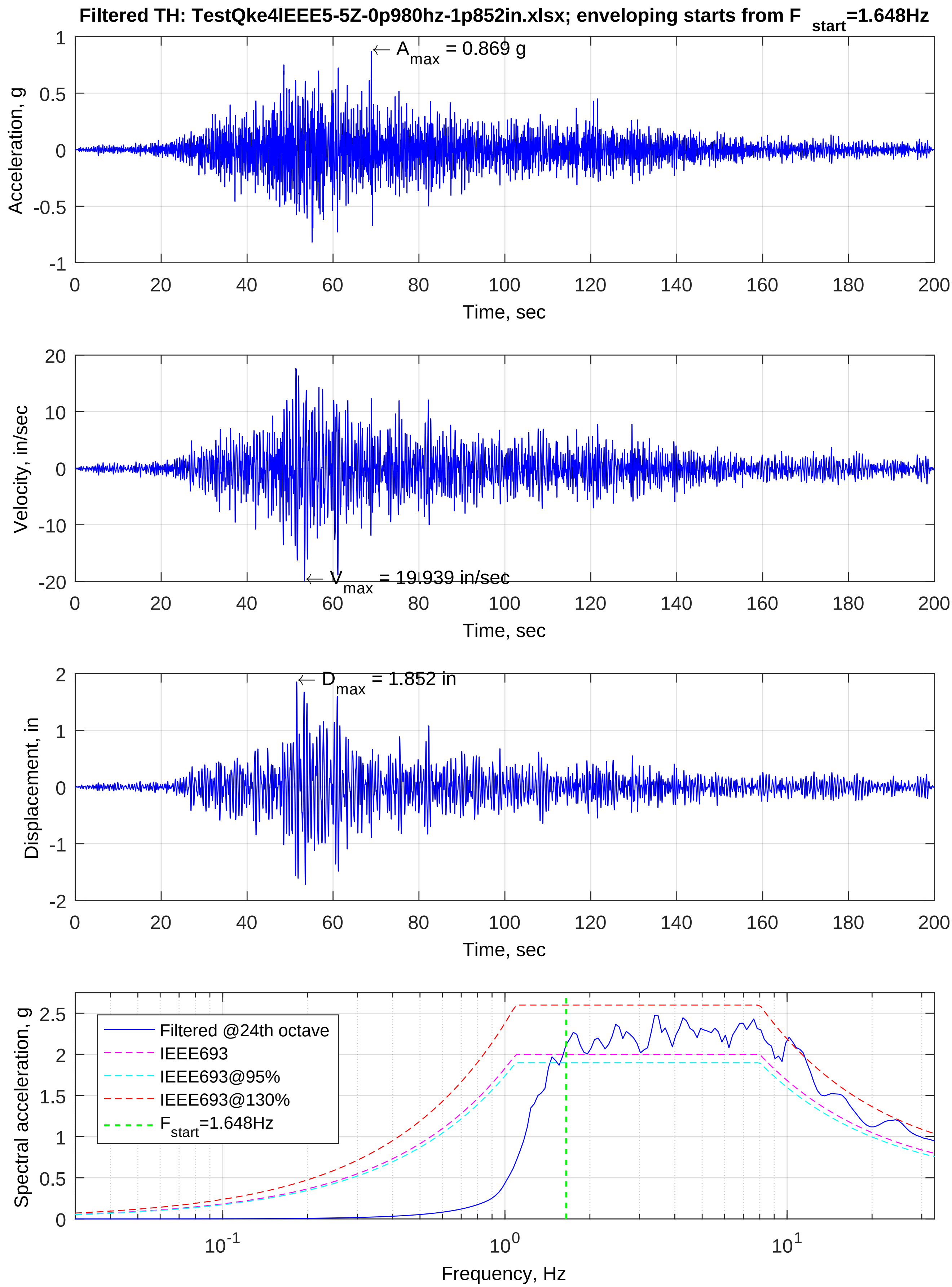

Figure B-30. Summary plots for TestQke4IEEE5-5Z-0p980hz-1p852in.xlsx

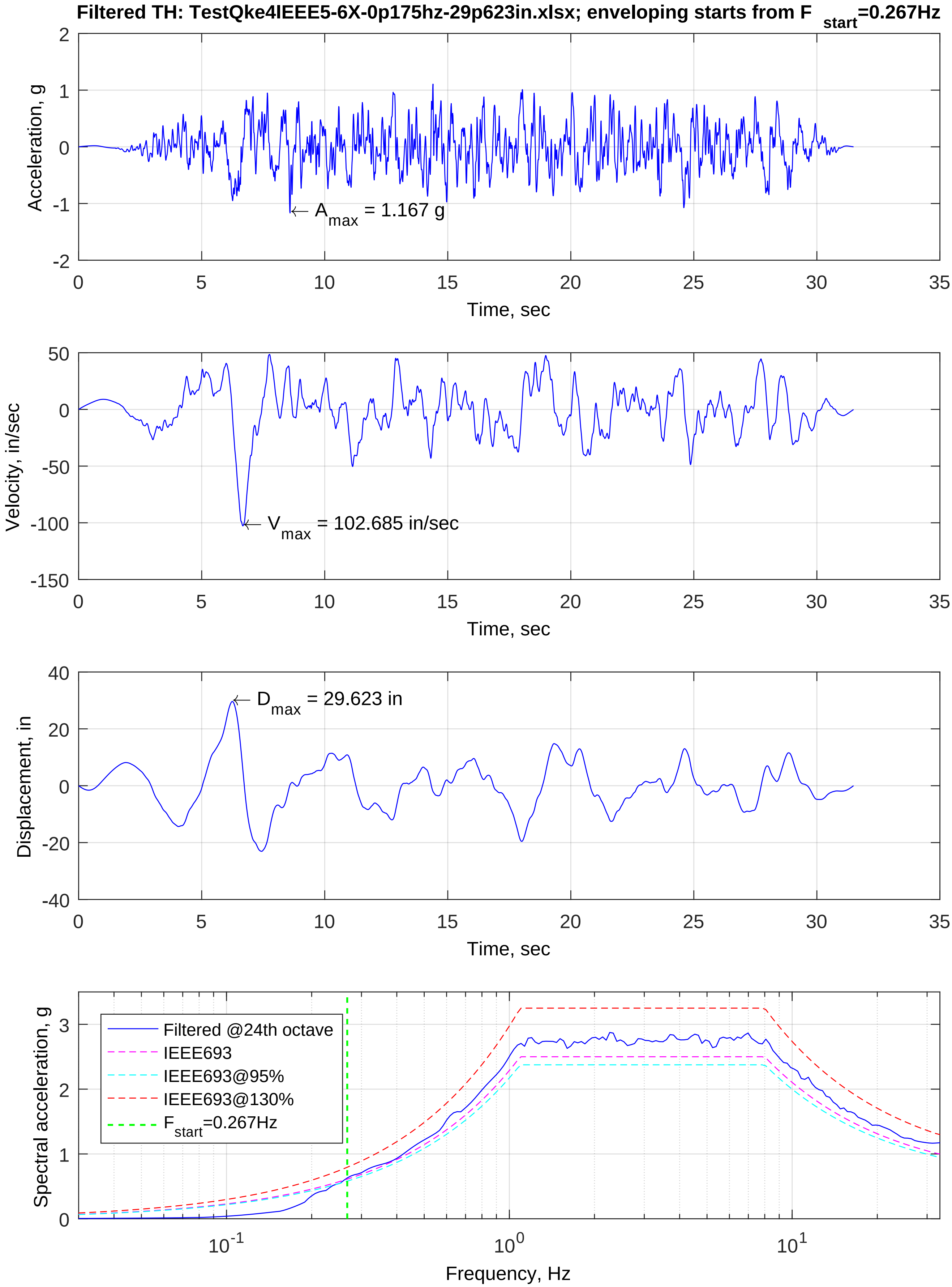

Figure B-31. Summary plots for TestQke4IEEE5-6X-0p175hz-29p623in.xlsx

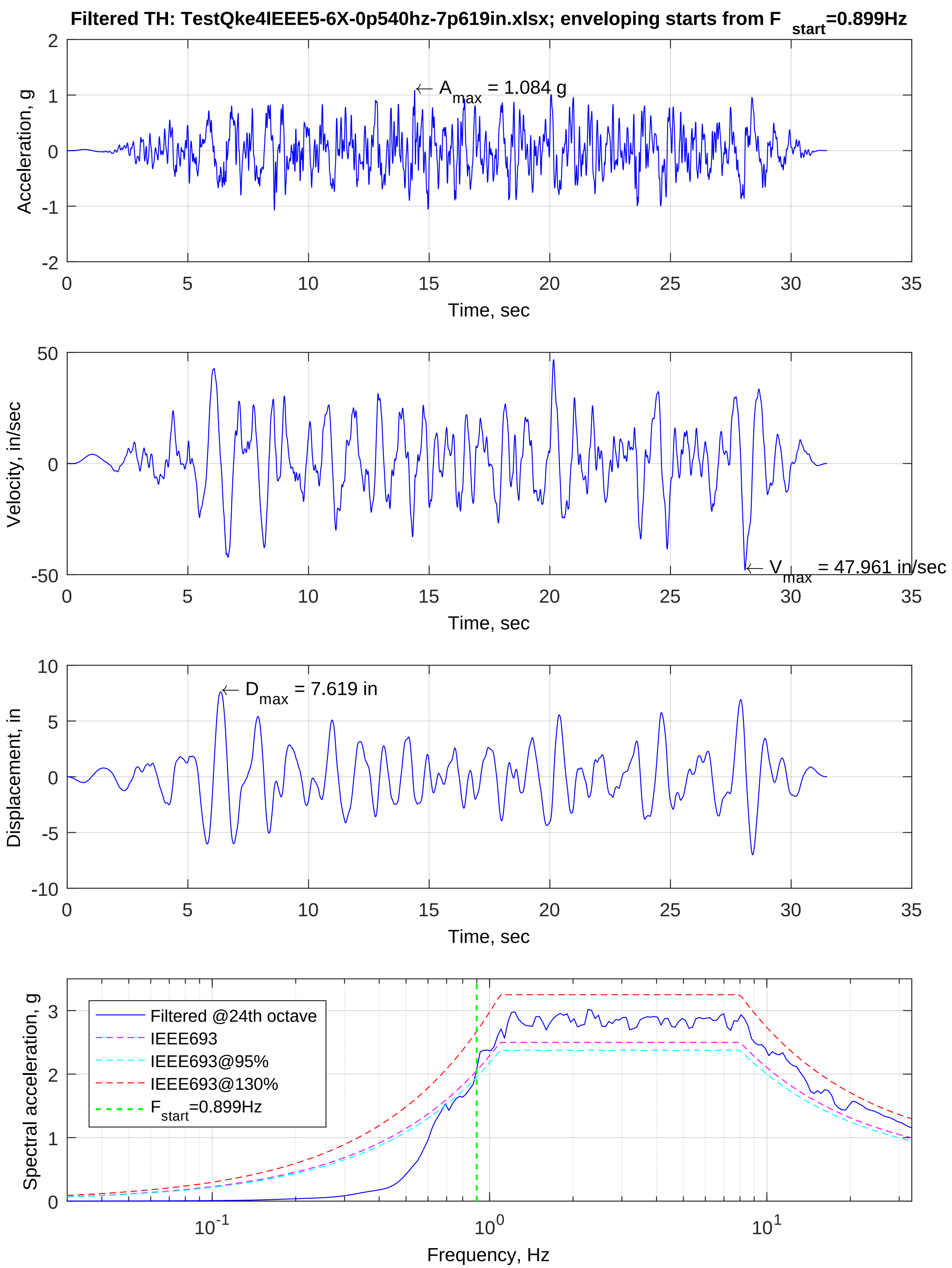

Figure B-32. Summary plots for TestQke4IEEE5-6X-0p540hz-7p619in.xlsx

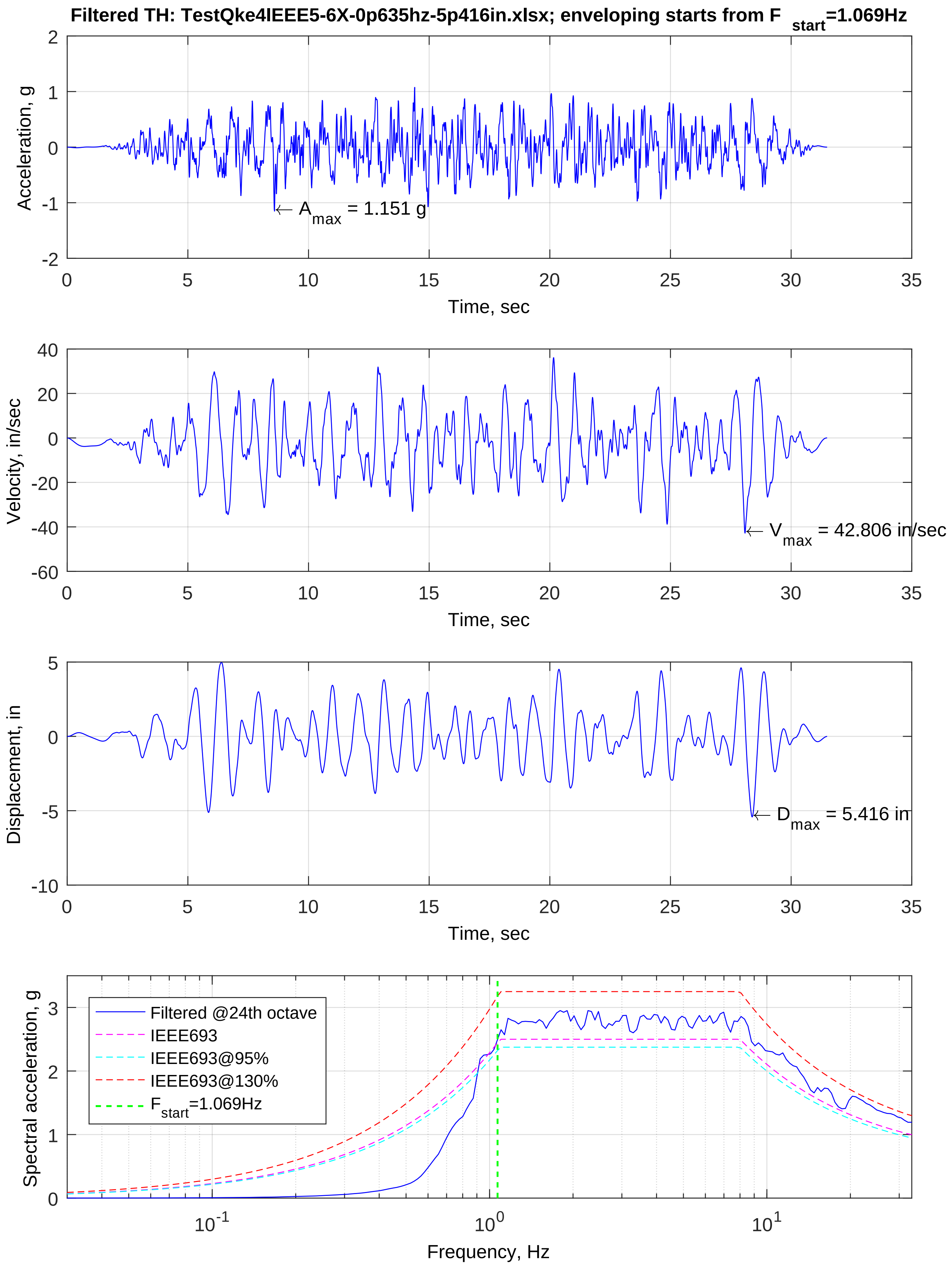

Figure B-33. Summary plots for TestQke4IEEE5-6X-0p635hz-5p416in.xlsx

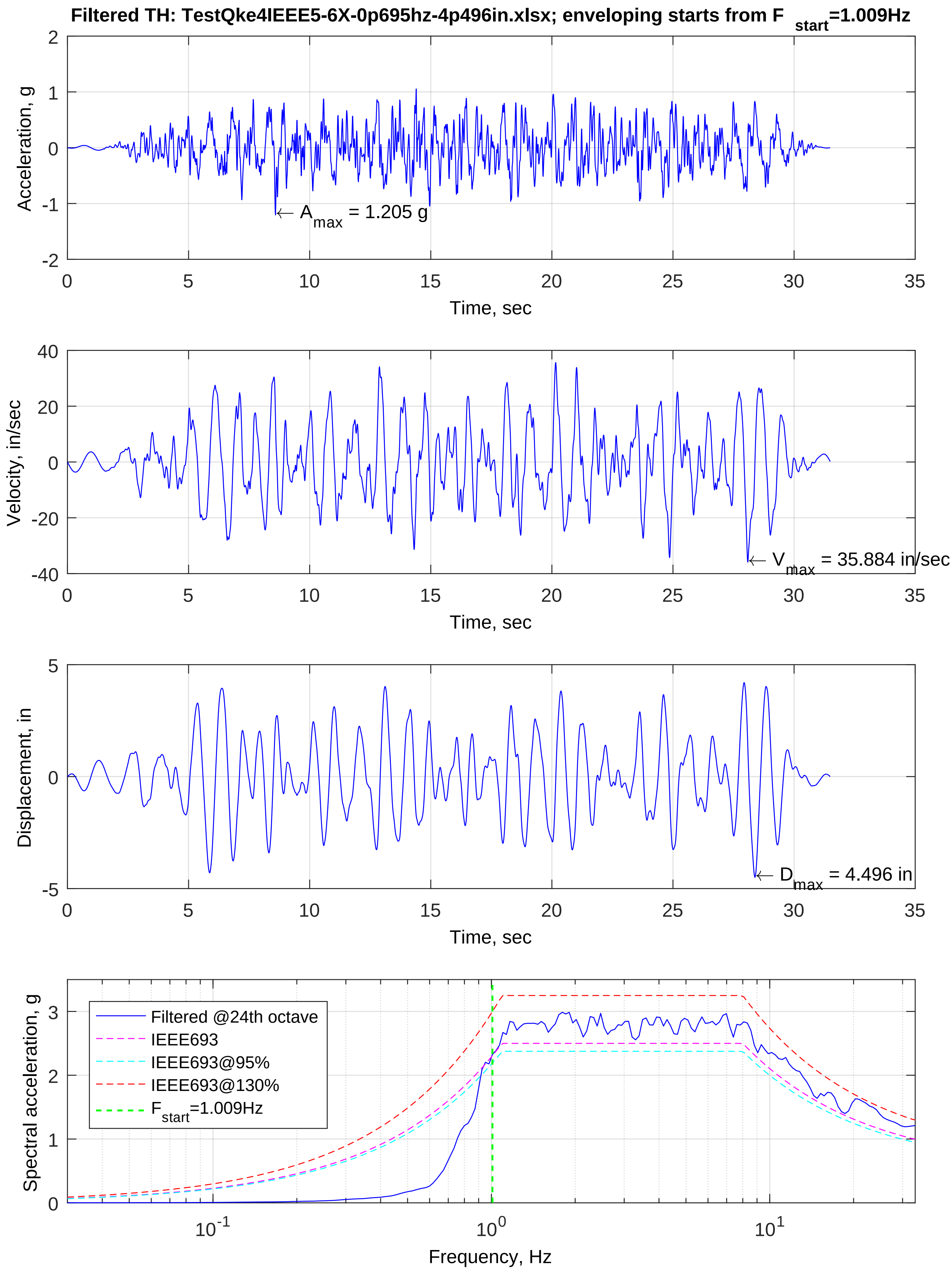

Figure B-34. Summary plots for TestQke4IEEE5-6X-0p695hz-4p496in.xlsx

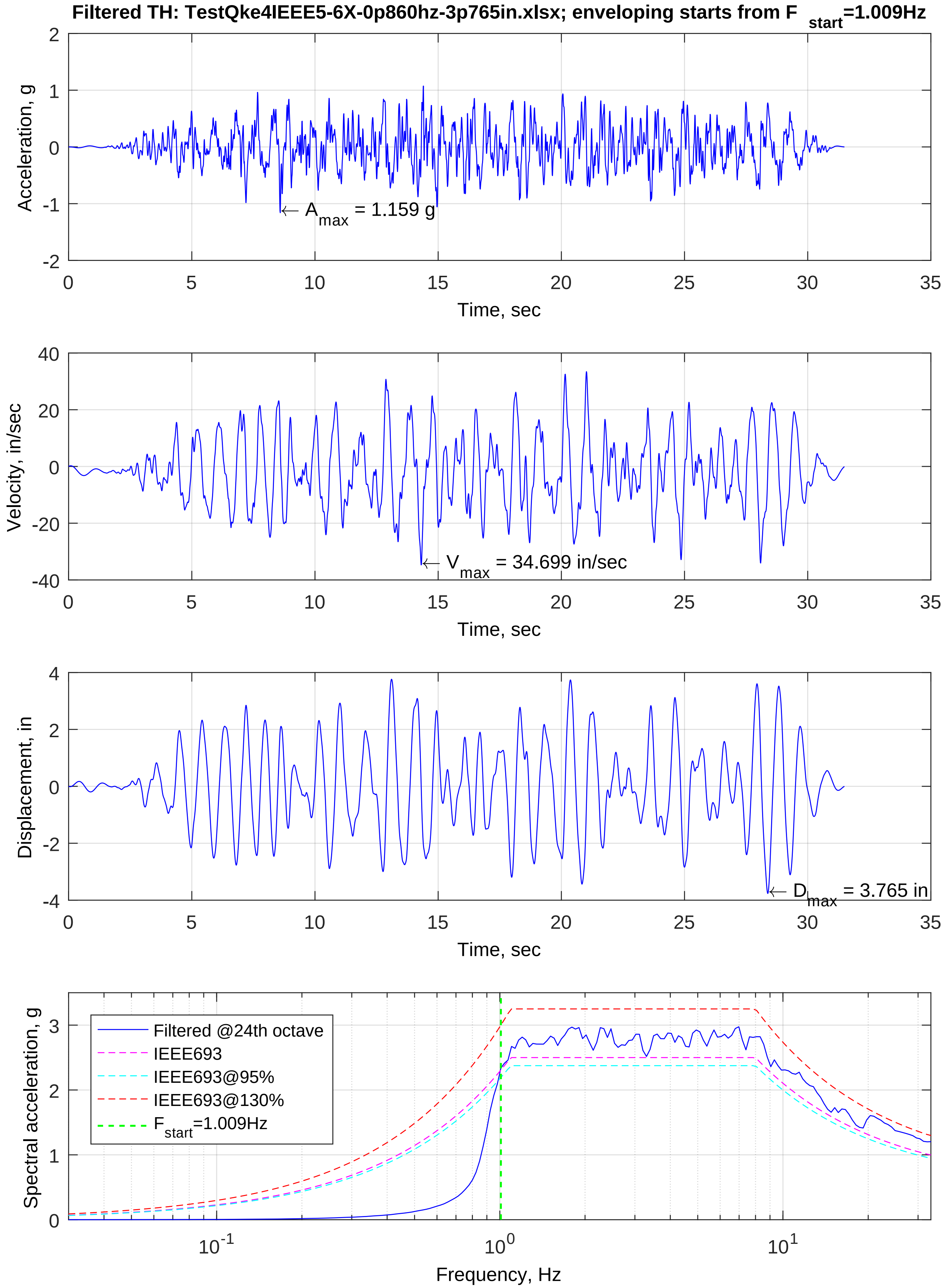

Figure B-35. Summary plots for TestQke4IEEE5-6X-0p860hz-3p765in.xlsx

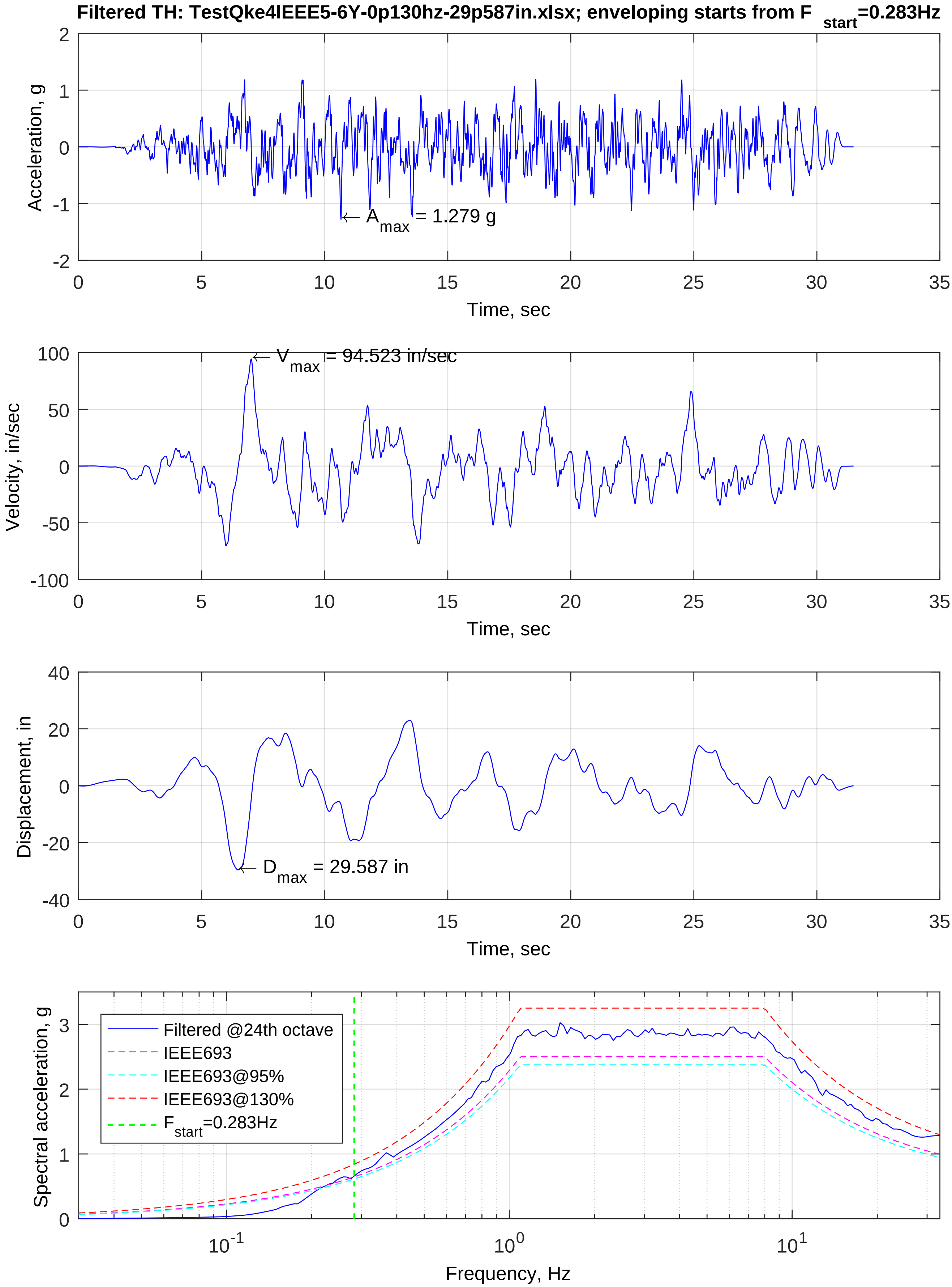

Figure B-36. Summary plots for TestQke4IEEE5-6Y-0p130hz-29p587in.xlsx

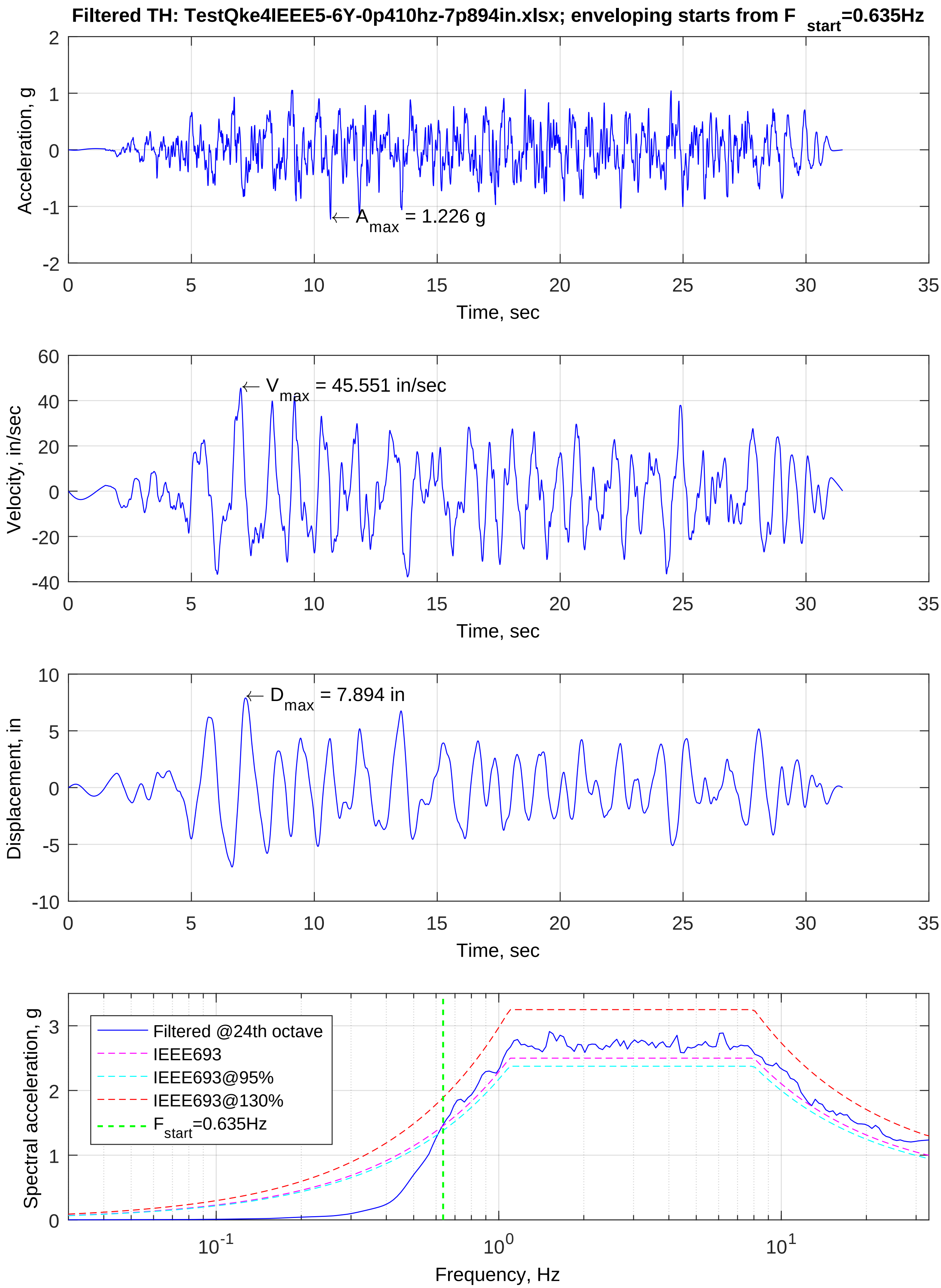

Figure B-37. Summary plots for TestQke4IEEE5-6Y-0p410hz-7p894in.xlsx

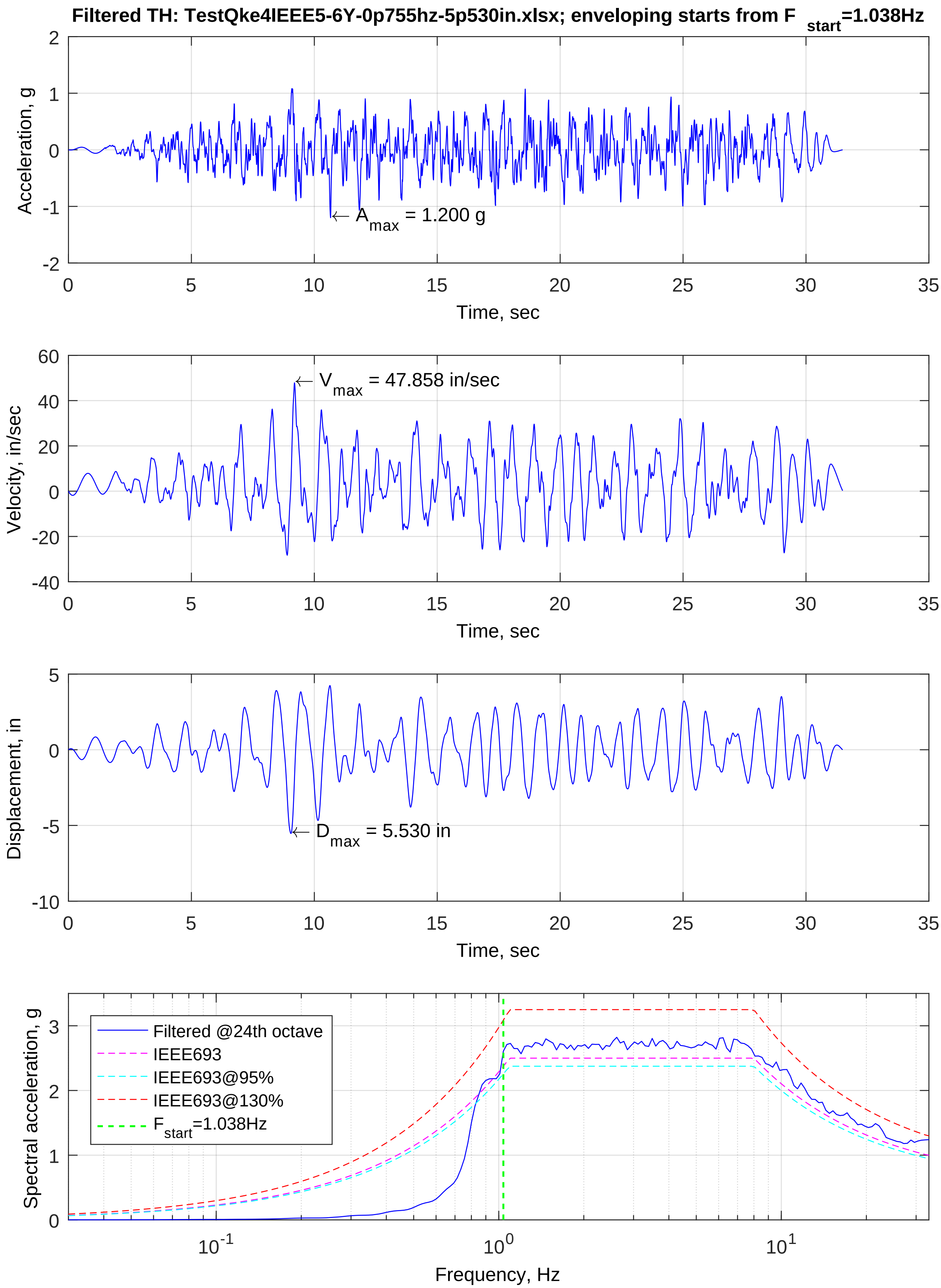

Figure B-38. Summary plots for TestQke4IEEE5-6Y-0p755hz-5p530in.xlsx

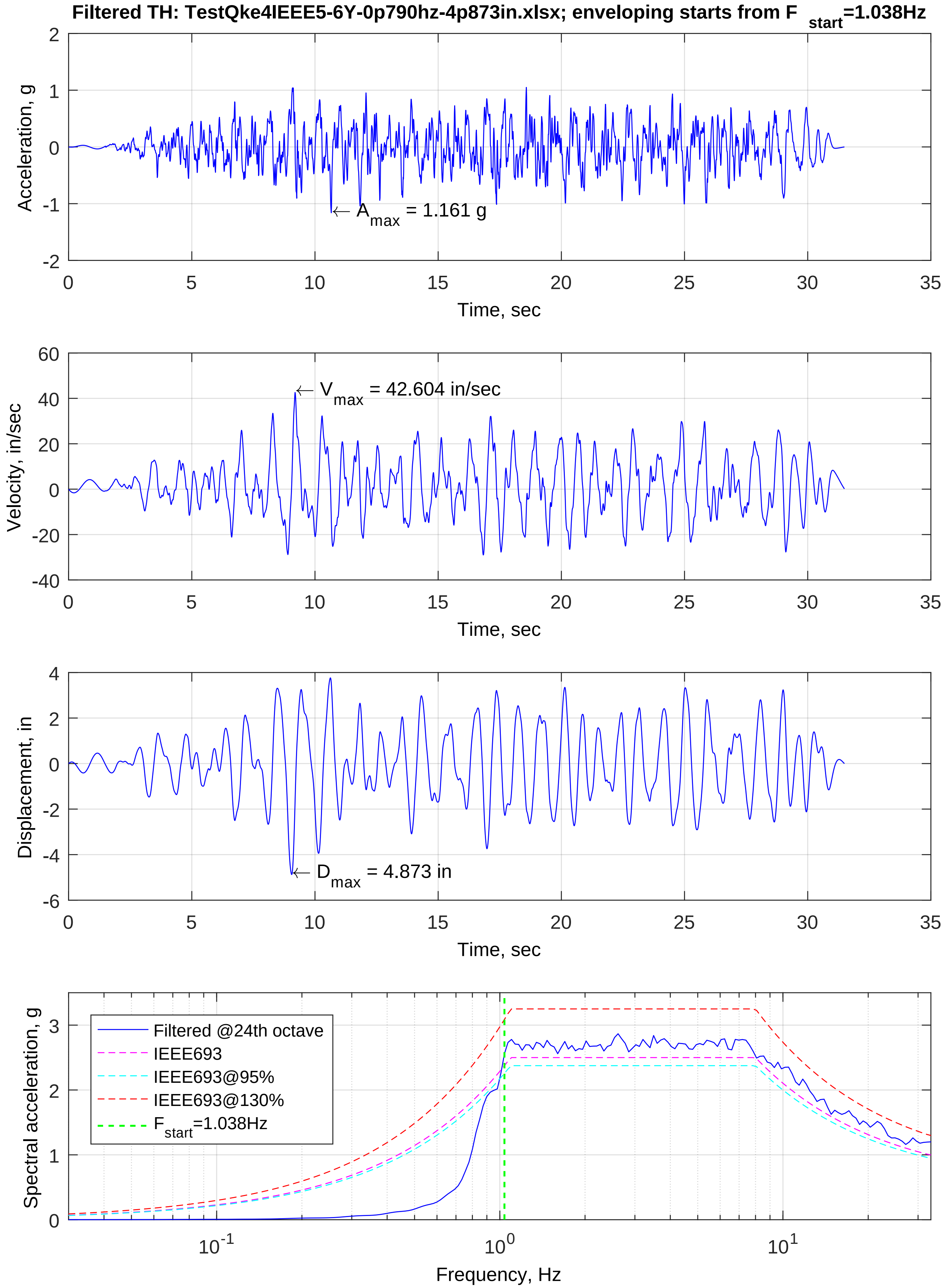

Figure B-39. Summary plots for TestQke4IEEE5-6Y-0p790hz-4p873in.xlsx

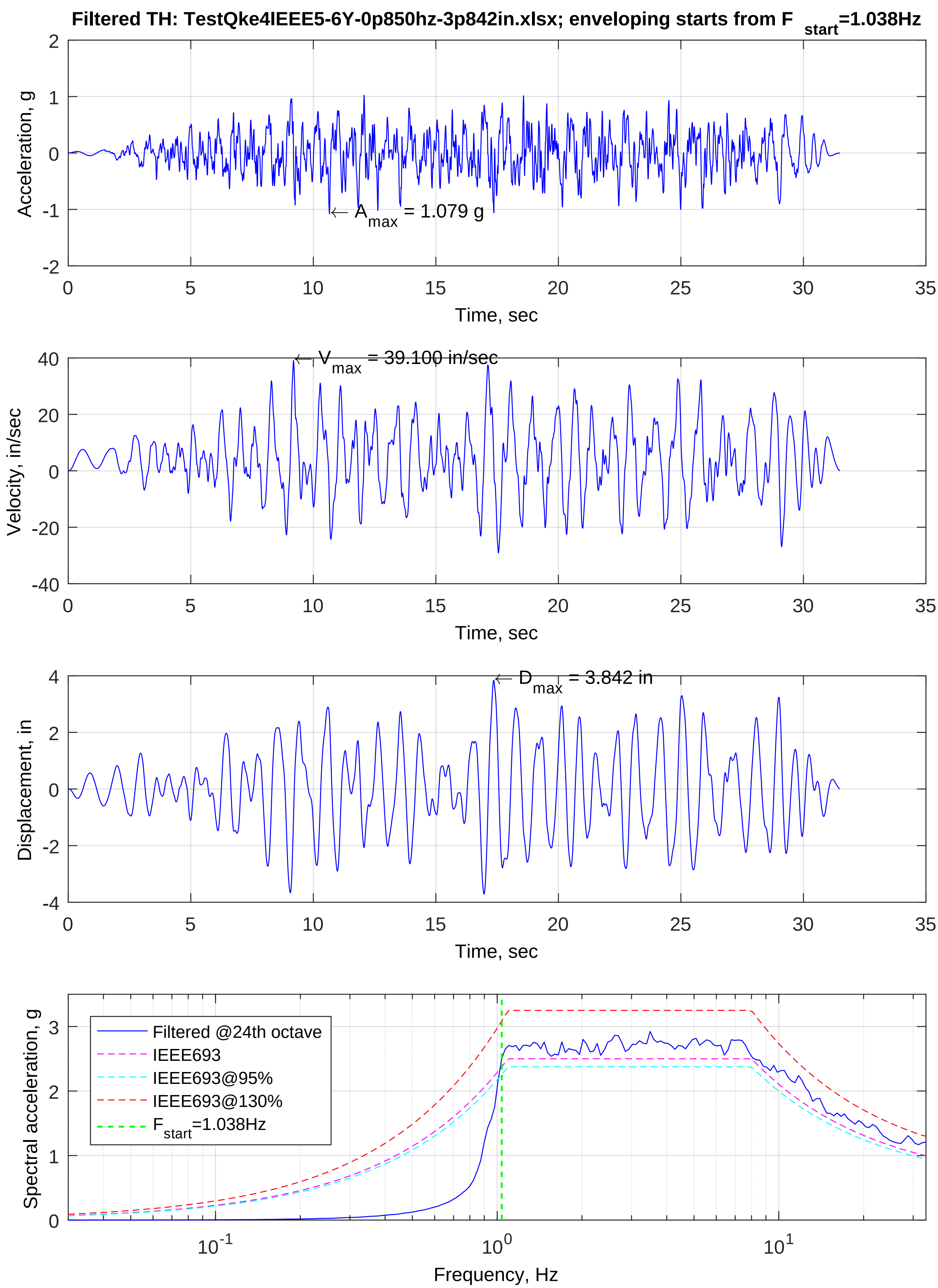

Figure B-40. Summary plots for TestQke4IEEE5-6Y-0p850hz-3p842in.xlsx

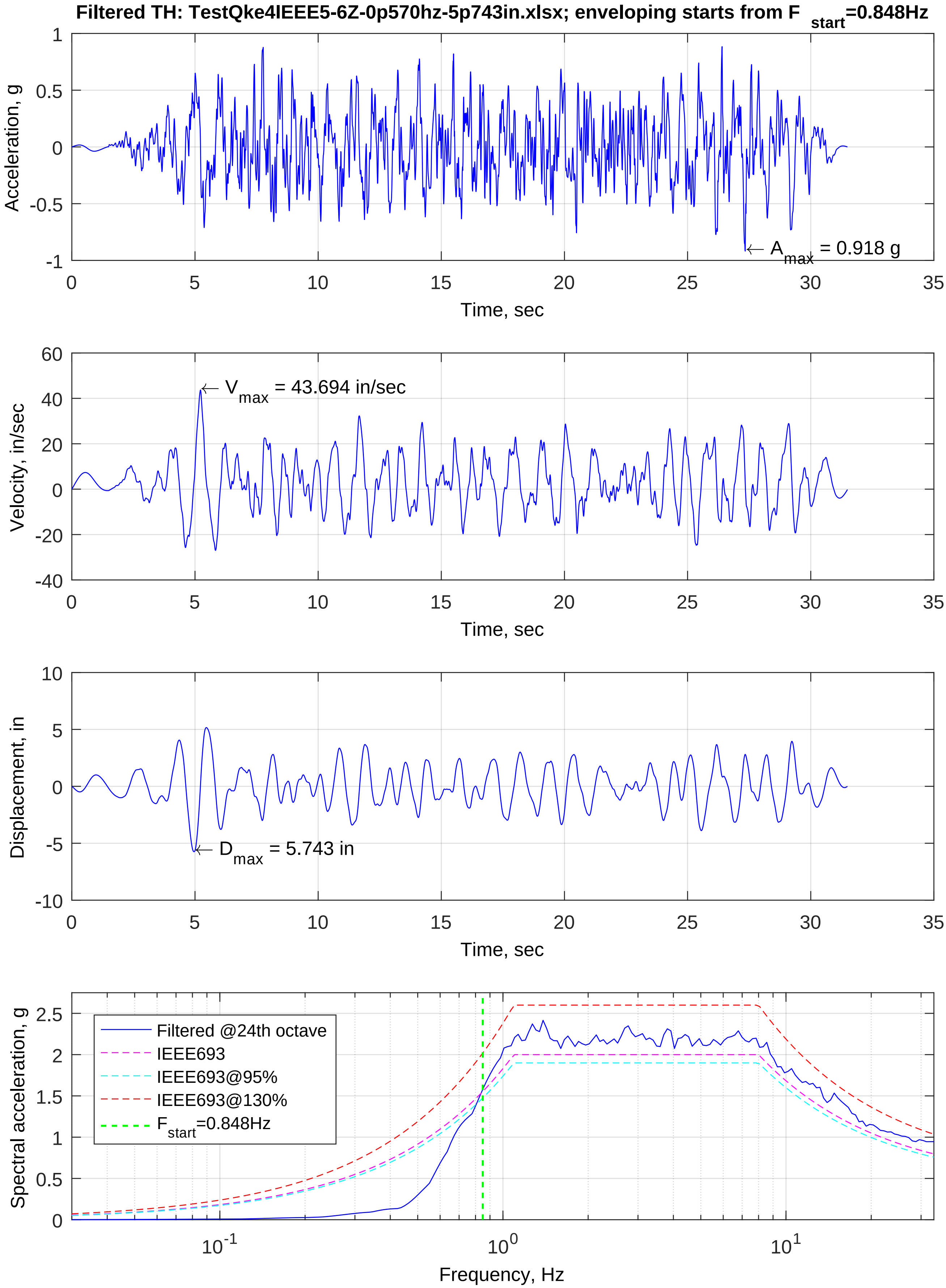

Figure B-41. Summary plots for TestQke4IEEE5-6Z-0p570hz-5p743in.xlsx

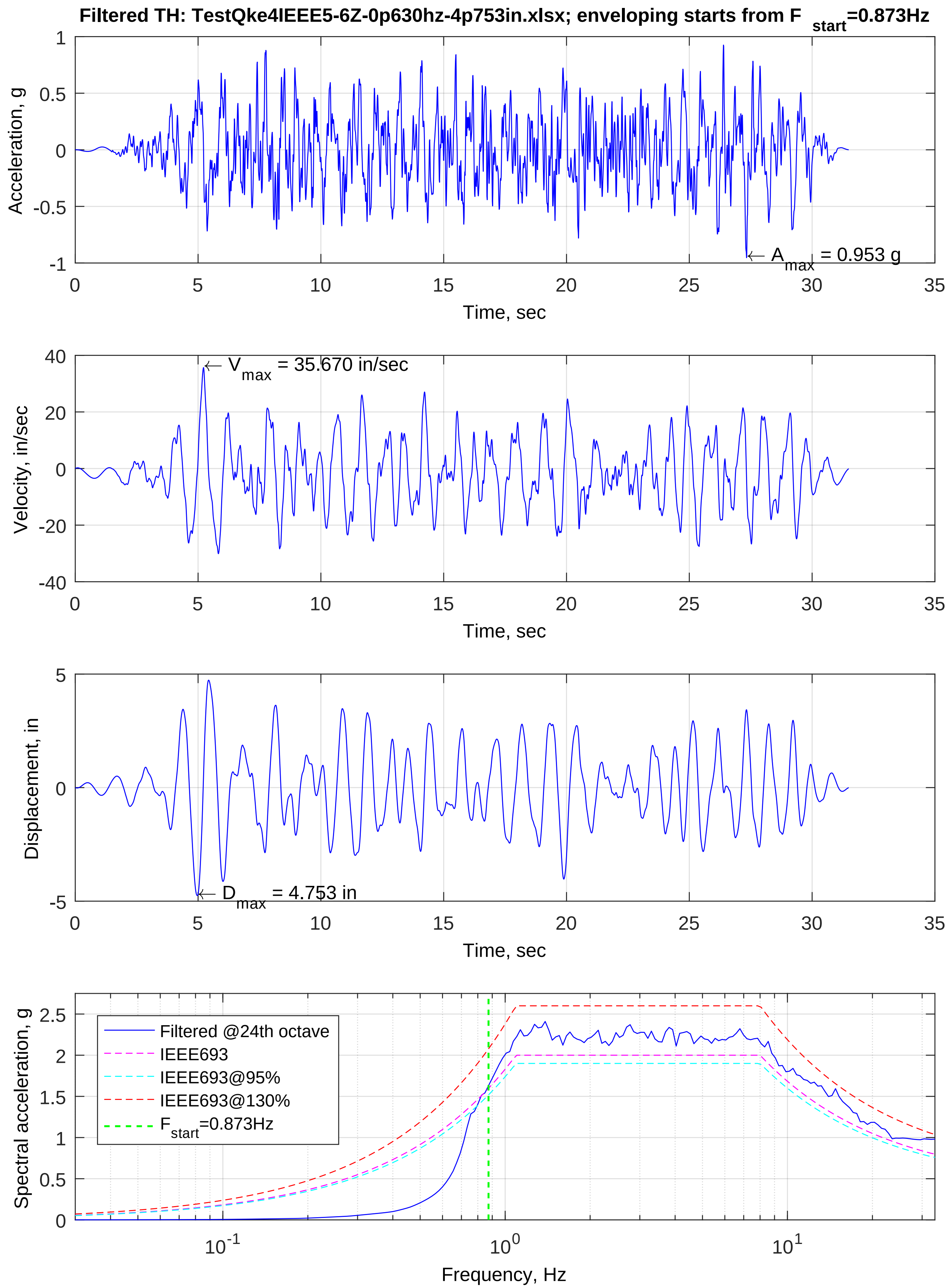

Figure B-42. Summary plots for TestQke4IEEE5-6Z-0p630hz-4p753in.xlsx

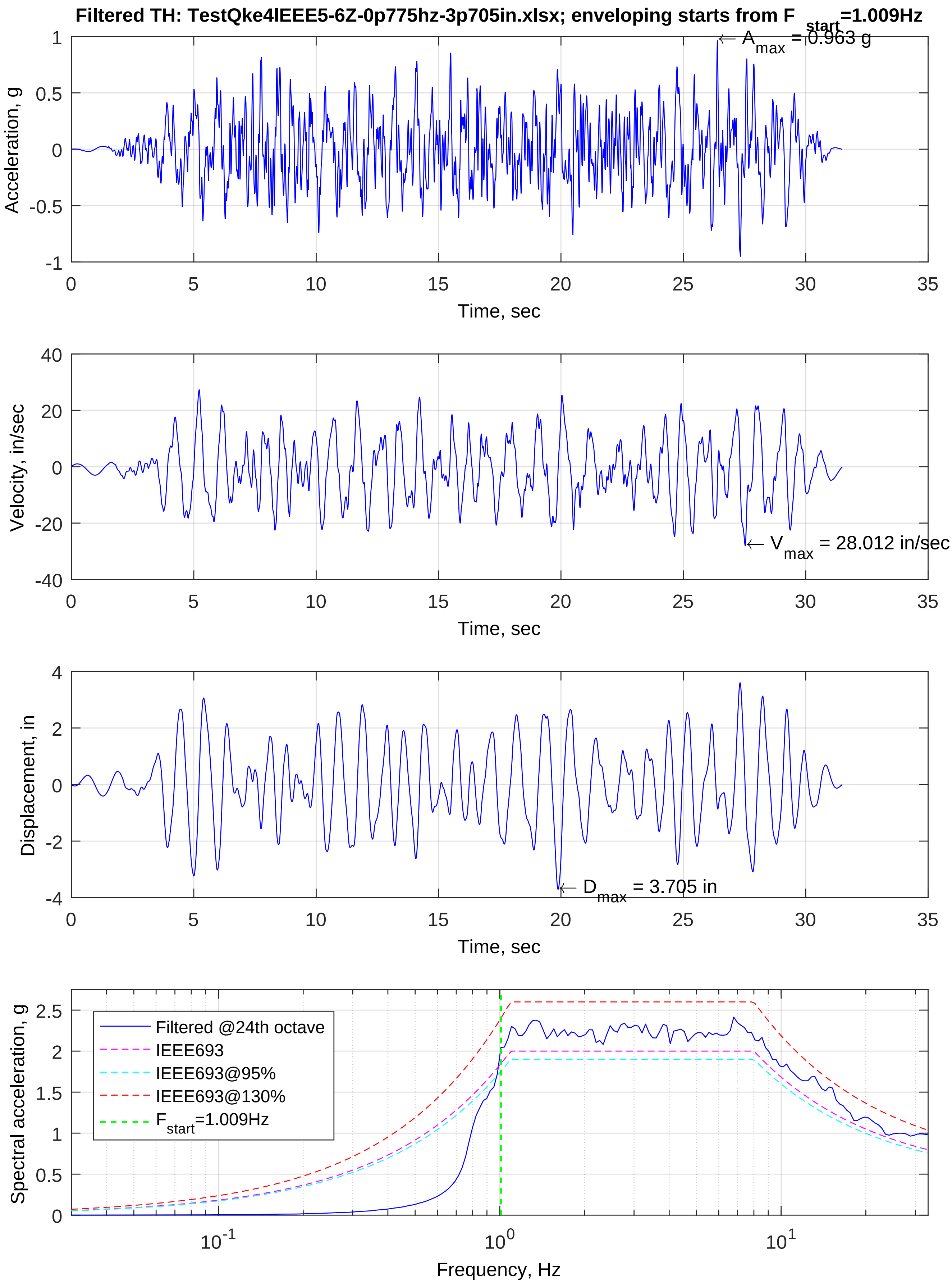

Figure B-43. Summary plots for TestQke4IEEE5-6Z-0p775hz-3p705in.xlsx

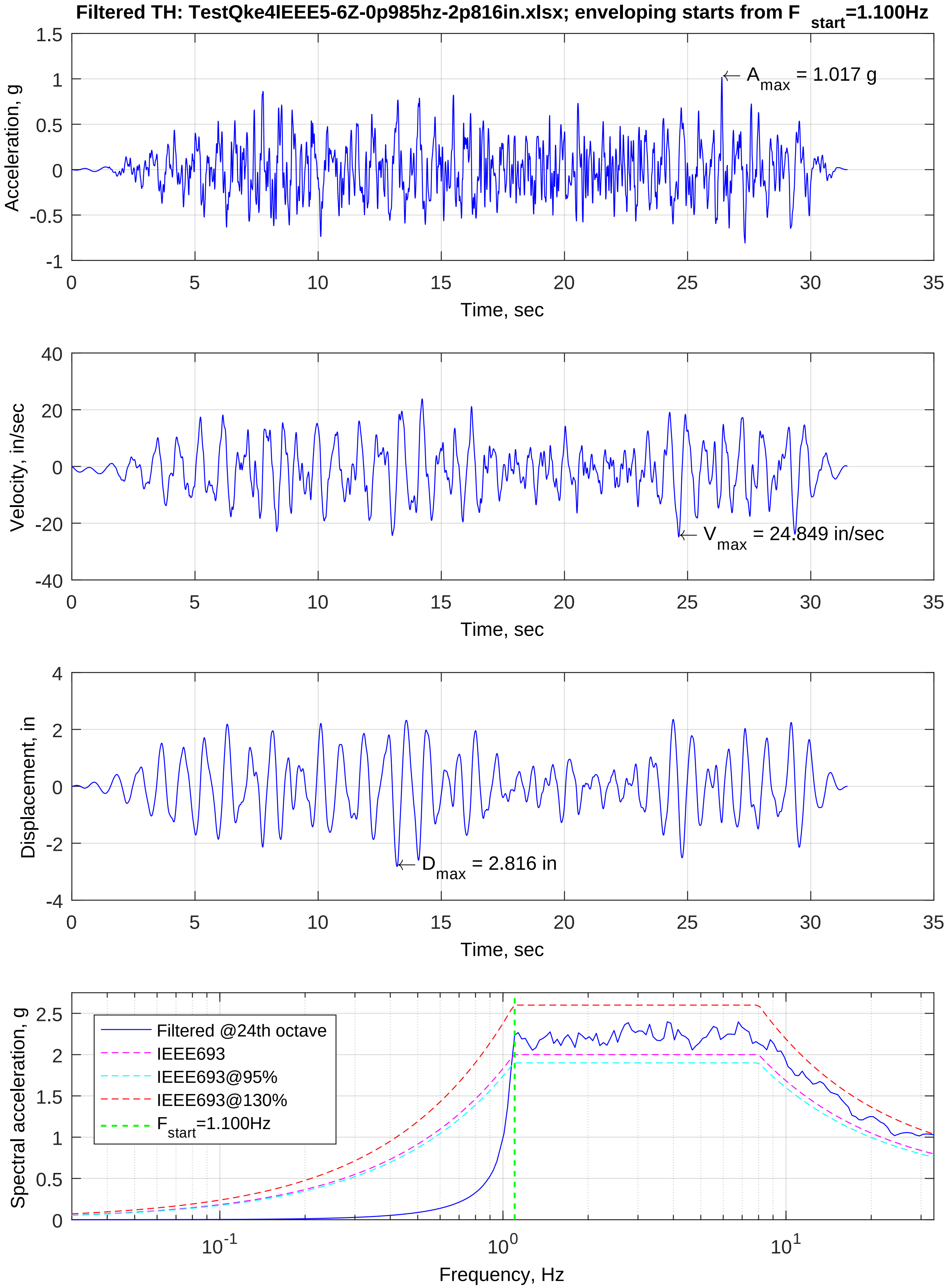

Figure B-44. Summary plots for TestQke4IEEE5-6Z-0p985hz-2p816in.xlsx

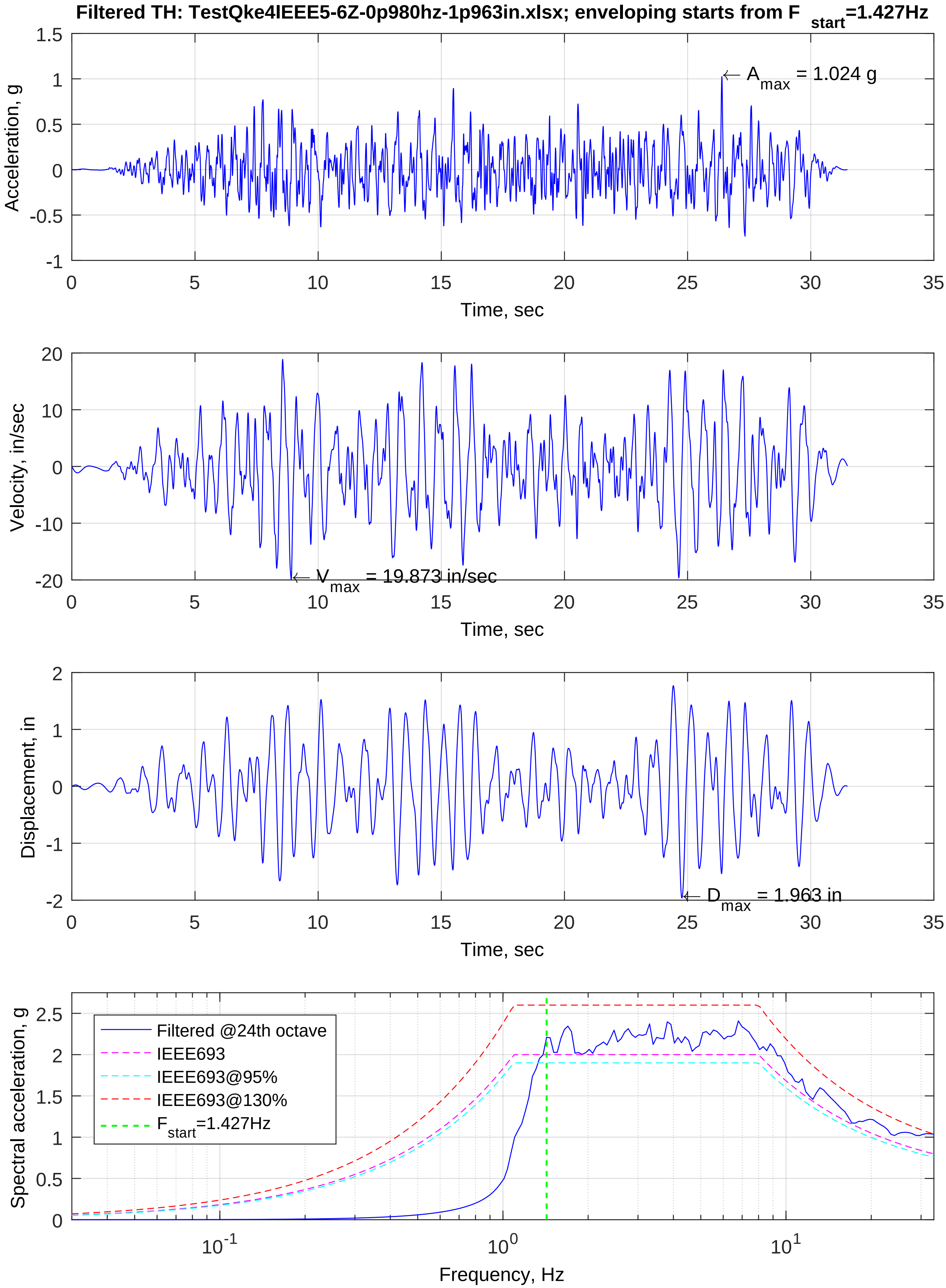

Figure B-45. Summary plots for TestQke4IEEE5-6Z-0p980hz-1p963in.xlsx