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MULTIPLE MODEL ADAPTIVE ESTIMATION
AND CONTROL REDISTRIBUTION PERFORMANCE
ON THE VISTA F-16
DURING PARTIAL ACTUATOR IMPAIRMENTS
VOLUME II

DTIC QUALITY INSPECTED 3

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY
AIR FORCE INSTITUTE OF TECHNOLOGY

19980210 120

Wright-Patterson Air Force Base, Ohio

AFIT/GE/ENG/97D-23

MULTIPLE MODEL ADAPTIVE ESTIMATION
AND CONTROL REDISTRIBUTION PERFORMANCE
ON THE VISTA F-16
DURING PARTIAL ACTUATOR IMPAIRMENTS

VOLUME II

THESIS

Curtis Steven Clark

AFIT/GE/ENG/97D-23

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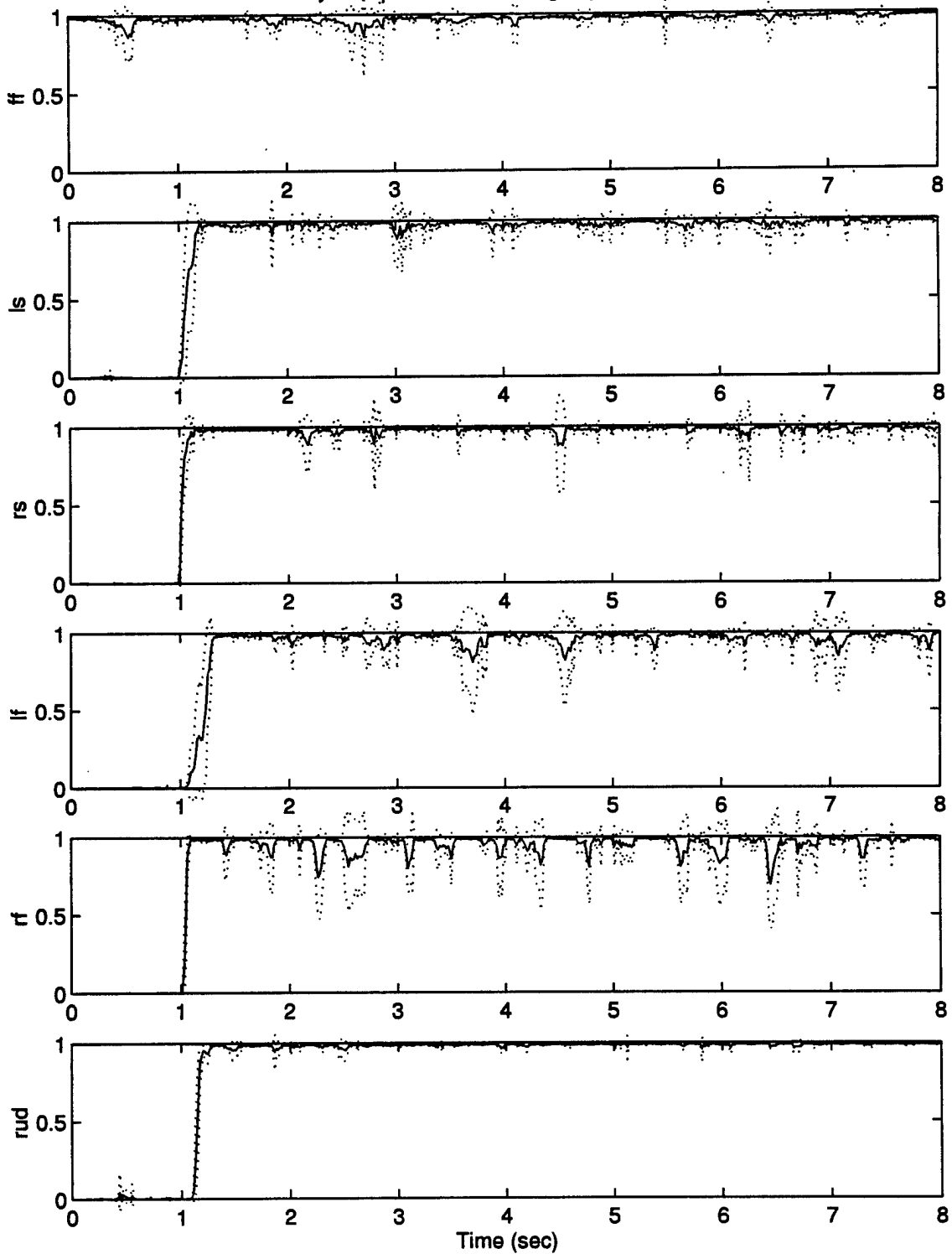
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Section SUM

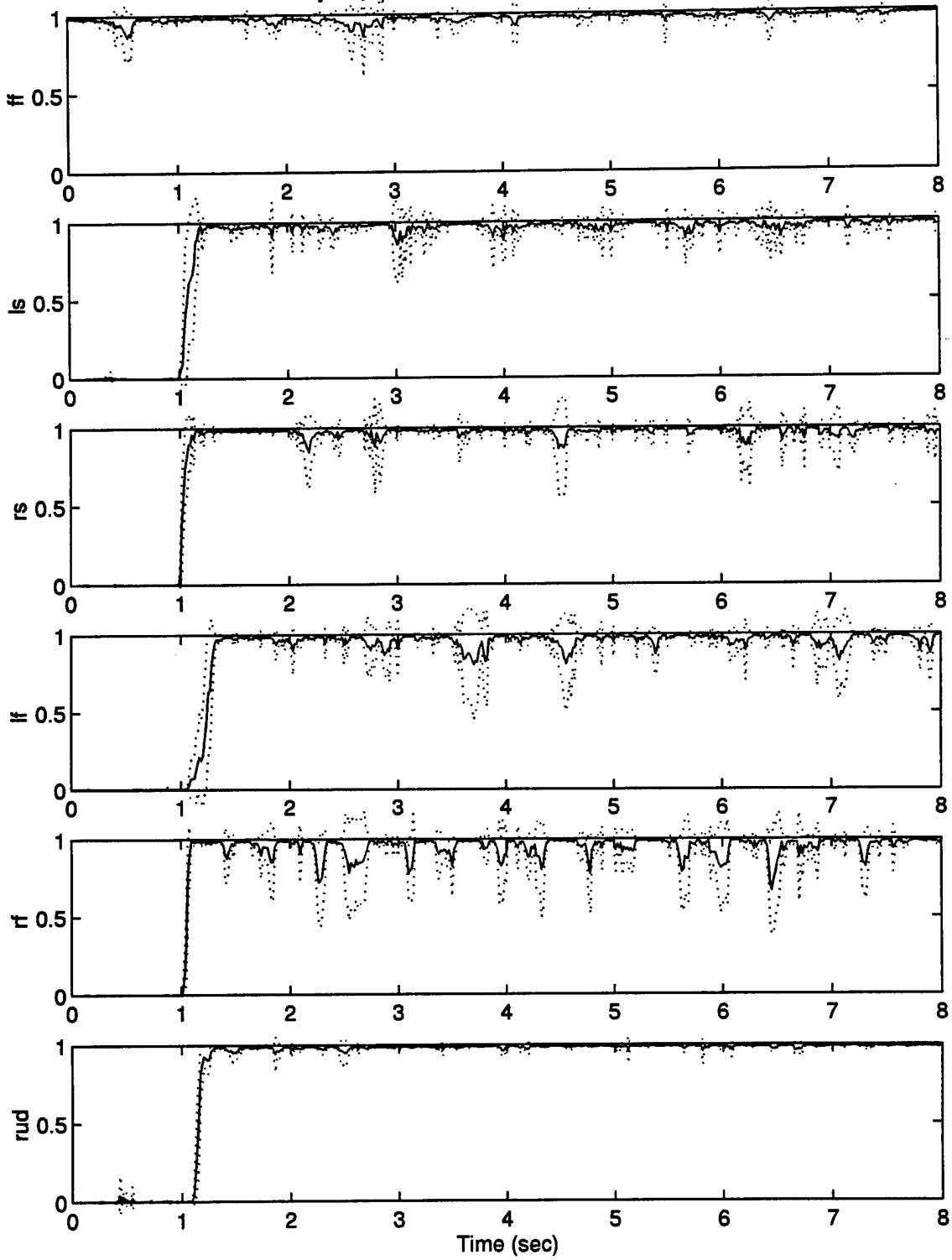
This section contains the Probability Summary Plots specified in Section 4.5.1 which were used to compile Table 4-1. The following table is a guide to the plots found in this section. The leftmost column lists the MMAE probability channels that are plotted (in parentheses), together with their meanings. The **Boldface** entries are the *plot data* titles (which were used for data indexing purposes) found within the full title at the top of each summary plot, and are listed in the order, from left to right in the bottom row of the table, that the plots are found in this section. As an example, the Probability Summary Plot for the partial actuator impairment cases with $\epsilon = .05$ (95% actuator impairment cases) is titled: "Summary Plot (with Mean +/- Sigma) for curt5: 10 runs"

PROBABILITY SUMMARY PLOTS FOR SINGLE CONTROL SURFACE PARTIAL IMPAIRMENTS: NO RECONFIGURATION, NO MANEUVER, DITHER 'ON'							
Control Surface	Actuator Effectiveness Factor, ϵ , at 1 second (0 = totally failed, 1 = fully functional)						
Fully Functional (ff)							
Left Stabilator (ls)	0	.05	.1	.15	.25	.50	.75
Right Stabilator (rs)	0	.05	.1	.15	.25	.50	.75
Left Flaperon (lf)	0	.05	.1	.15	.25	.50	.75
Right Flaperon (rf)	0	.05	.1	.15	.25	.50	.75
Rudder (rud)	0	.05	.1	.15	.25	.50	.75
Summary Plot Title	curt0	curt5	curt10	curt15	curt25	curt50	curt75

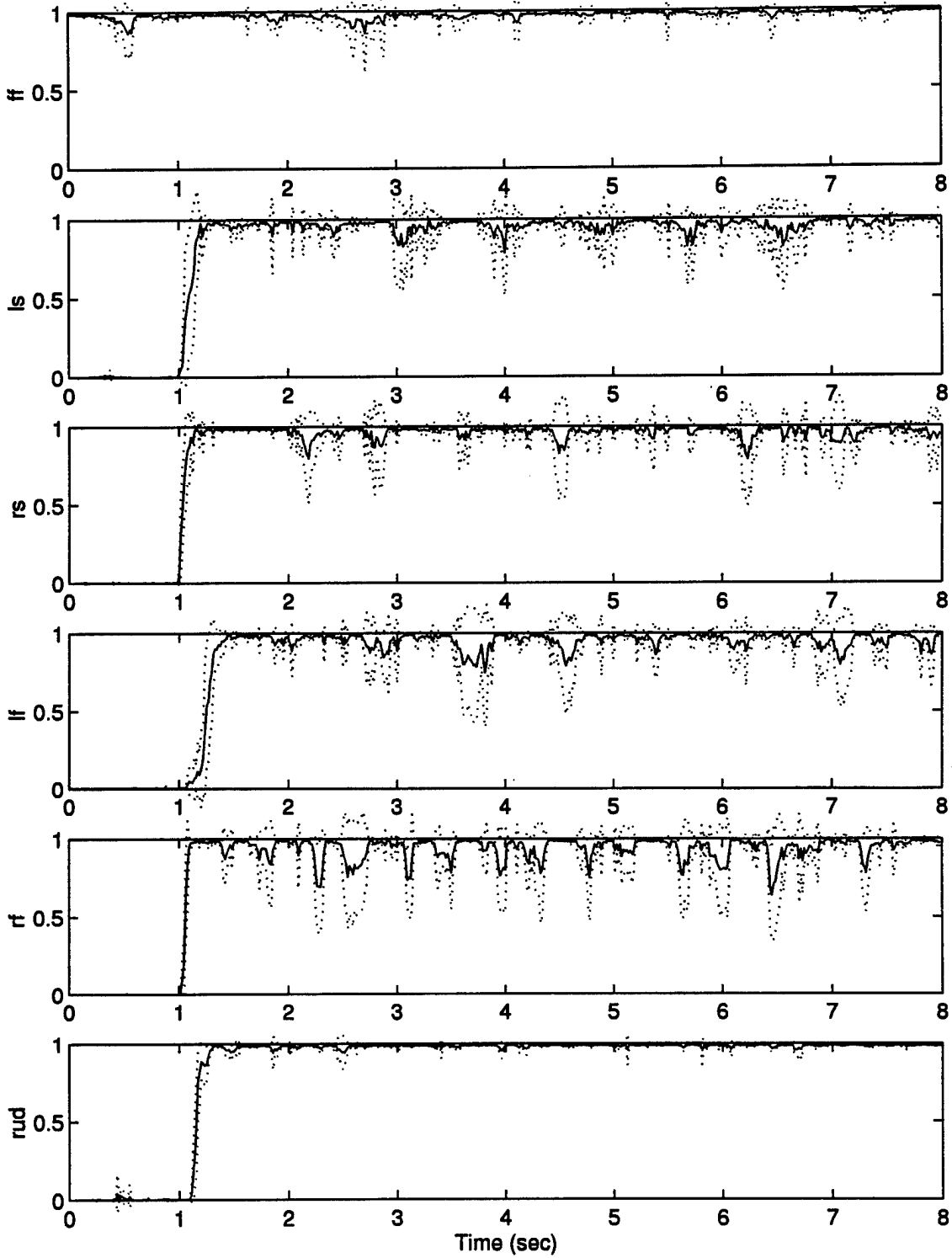
Summary Plot (with Mean \pm Sigma) for curt0: 10 runs



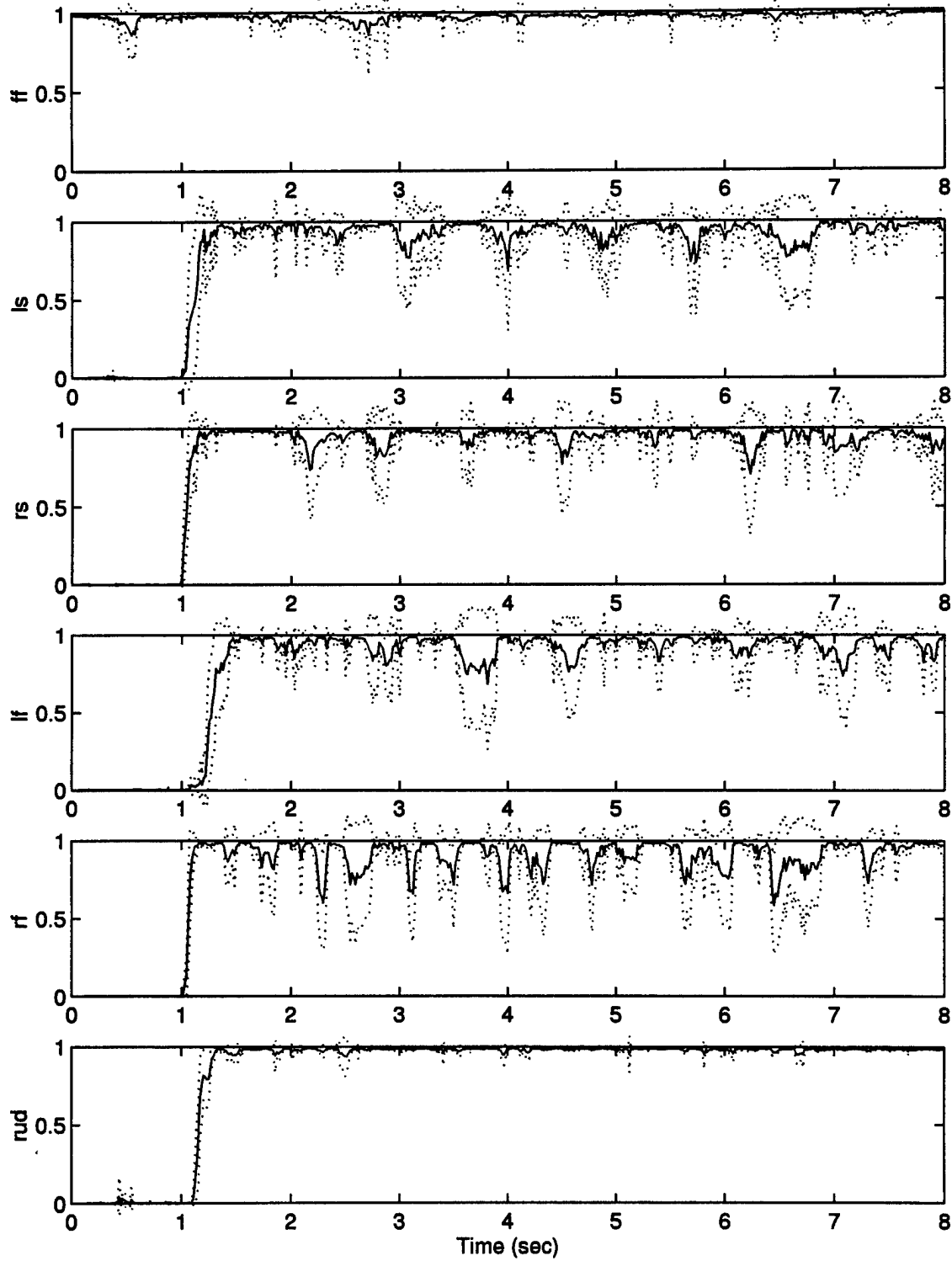
Summary Plot (with Mean \pm Sigma) for curt5: 10 runs



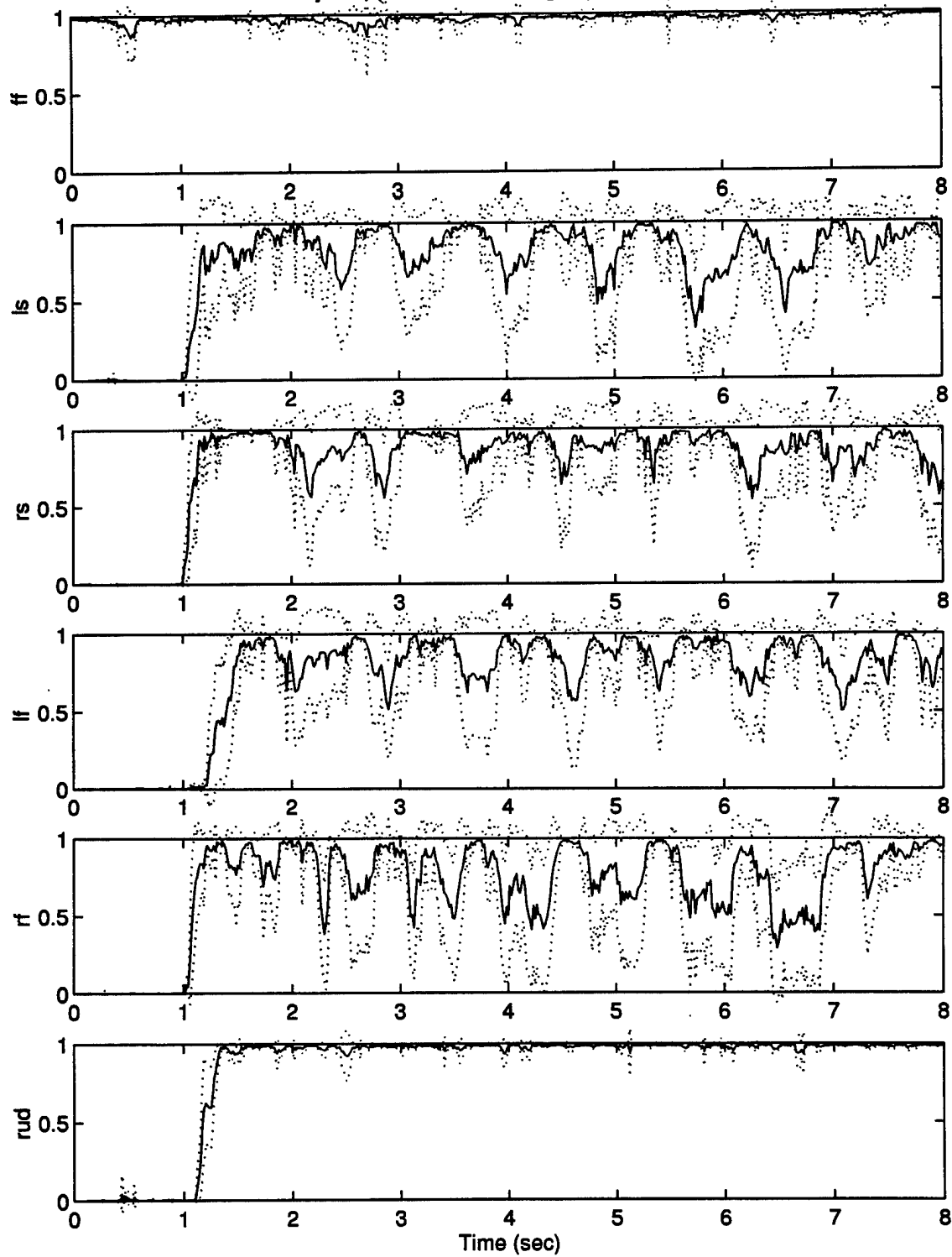
Summary Plot (with Mean \pm Sigma) for curt10: 10 runs



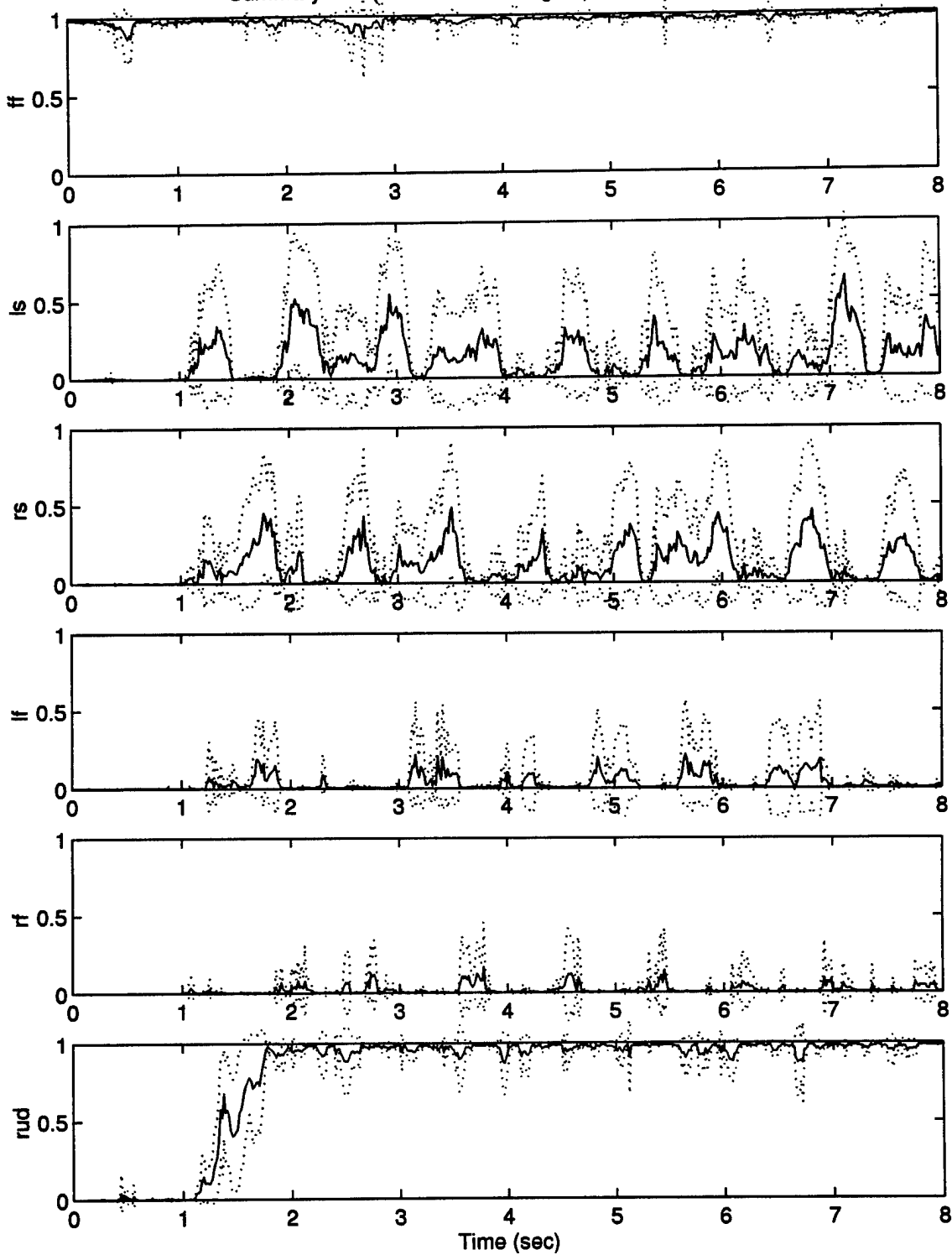
Summary Plot (with Mean \pm Sigma) for curt15: 10 runs



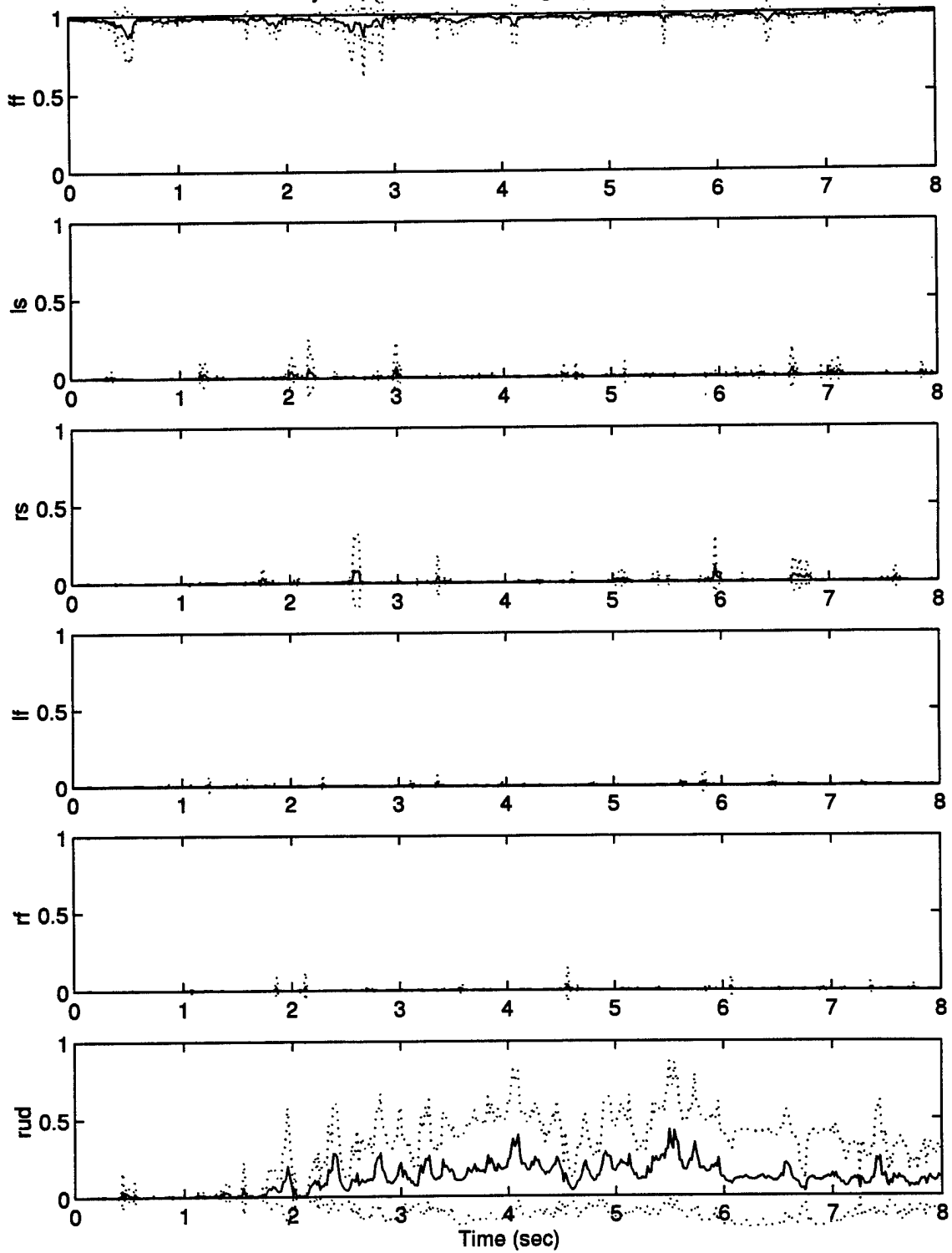
Summary Plot (with Mean \pm Sigma) for curt25: 10 runs



Summary Plot (with Mean \pm Sigma) for curt50: 10 runs



Summary Plot (with Mean \pm Sigma) for curt75: 10 runs



Appendix M: An Alternative Control Reconfiguration Method

For Cases of Partial Actuator Impairment

In cases of partial actuator impairment ($0 < \epsilon < 1$), the direct pseudoinverse calculation (Equation (3-35)) is equal to the true inverse calculation: F_{ai}^{-1} . The true inverse calculation will command the partially impaired actuator to $1/\epsilon$ times the original command, and, as ϵ assumes values less than 0.5 (50% actuator failure or greater) this may cause actuators to be commanded to rate and/or position saturations. Maybeck [37] has suggested an alternative to computing and using F_{ai}^{-1} (Section 3.9.2), in cases of partial impairments, which would simplify redistribution calculations and *perhaps* prevent rate and position saturations of remaining actuators.

The alternative to using the true inverse calculation, F_{ai}^{-1} , for *partially* impaired actuators is to use a variant of the pre-packed D_{ai} matrix (Equation (3-37)) for *totally* failed actuators. Given a partial impairment of the i^{th} actuator such that its effectiveness is ϵ , the procedure is to multiply all j elements ($j \neq i$) in column ' i ' of D_{ai} by ϵ . The command to the impaired actuator ($j = i$) is equal to 1.0, and all *other* columns of " D_{ai} variant" contain ones on the diagonal. It can be proven [49] that this alternative method satisfies Equation (3-32). An example is given for the case of a 70% left stabilator ($i=1$) actuator impairment (actuator effectiveness, $\epsilon = .3$). The desired condition is expressed by Equations (3-30) and (3-32):

$$\mathbf{B}_{fail} \mathbf{u}_r \approx \mathbf{B} \mathbf{u} \quad (3-30)$$

$$\mathbf{u}_r = \mathbf{D}_{ai} \mathbf{u} \quad (3-32)$$

For the impairment case specified, Equation (3-36) applies and results in:

$$\mathbf{D}_{ai} = \mathbf{F}_{ai}^{-1} = \begin{bmatrix} 3.3 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

The alternative method for this case is to take the fully-failed Control Reconfiguration matrix, \mathbf{D}_{a1} , for the left stabilator:

$$\mathbf{D}_{a1} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ +0.906 & 0 & 1 & 0 & 0 \\ -0.906 & 0 & 0 & 1 & 0 \\ +0.786 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Entry (1,1) is set equal to 1.0 (to generate a full command to the left stabilator, to which you anticipate a response with 70% effectiveness) and all other entries in the first column (column $i = 1$) are multiplied by 0.3 ($\epsilon = .3$), to distribute the required additional 30% effectiveness among the unfailed actuators, to yield:

$$\mathbf{D}_{a1 \text{ variant}} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0.3 & 1 & 0 & 0 & 0 \\ +0.2718 & 0 & 1 & 0 & 0 \\ -0.2718 & 0 & 0 & 1 & 0 \\ +0.2358 & 0 & 0 & 0 & 1 \end{bmatrix}$$

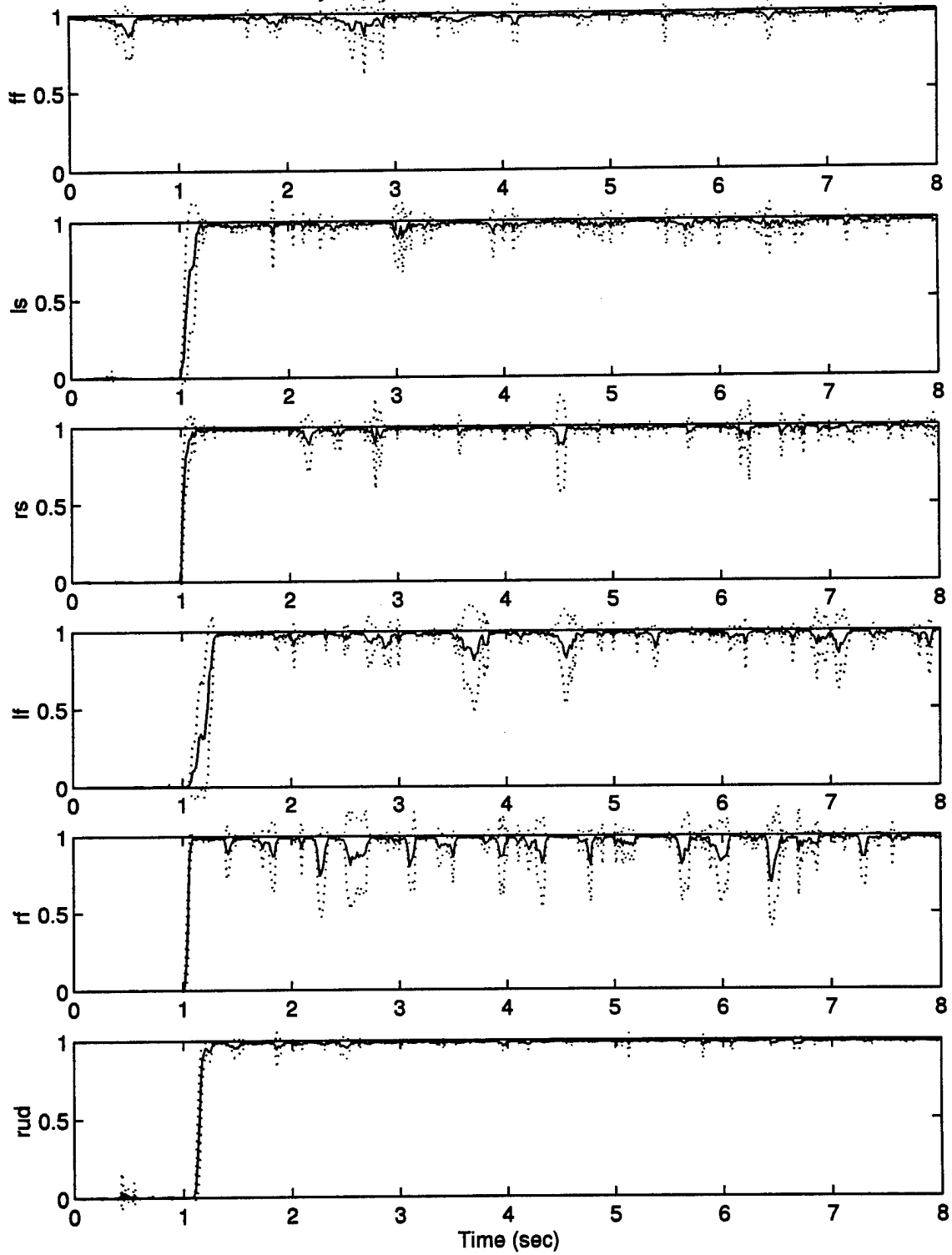
This result inserted into Equation (3-32) satisfies Equation (3-30), and may prevent the left stabilator from being "overdriven" into rate or position saturation.

*Appendix A.1: Single Total Actuator Impairments ($\epsilon = 0$), Control Redistribution 'OFF', Dither
'ON', No Maneuvers*

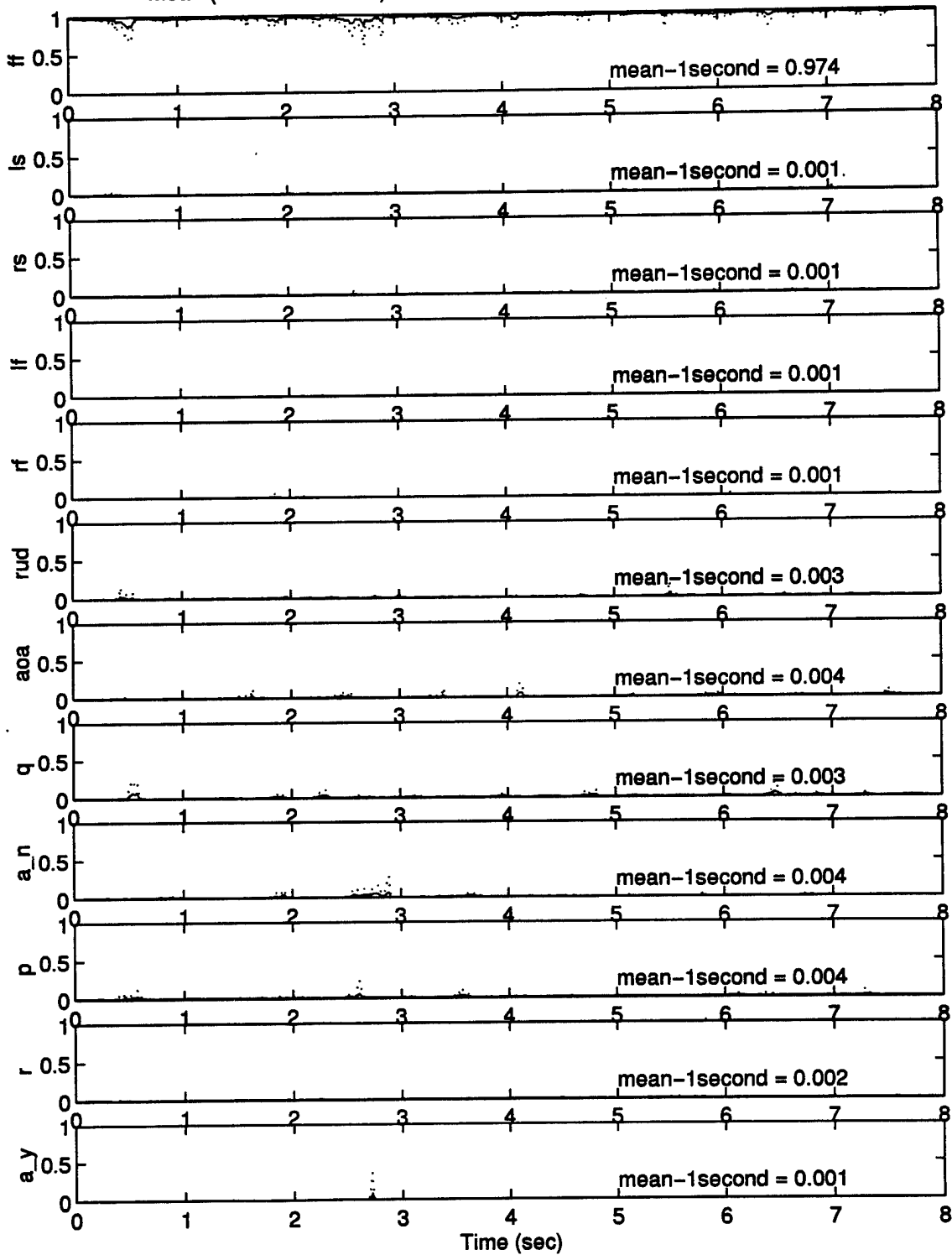
This appendix contains the Probability Summary Plot and individual probability plots for cases of single, total (100%) actuator impairments, without aircraft maneuvering or Control Reconfiguration (Redistribution), but with control dithering (Sections 4.5 and 4.11.1). The following table reviews the MMAE channel abbreviations found on the plots, together with their meanings:

MMAE Channel Abbreviation	Filter Hypothesis (Actuators)	MMAE Channel Abbreviation	Filter Hypothesis (Sensors)
ff	Fully Functional	aoa	Angle-of-Attack
ls	Left Stabilator	q	Pitch Rate
rs	Right Stabilator	a_n	Normal Acceleration
lf	Left Flaperon	p	Roll Rate
rf	Right Flaperon	r	Yaw Rate
rud	Rudder	a_y	Lateral Acceleration

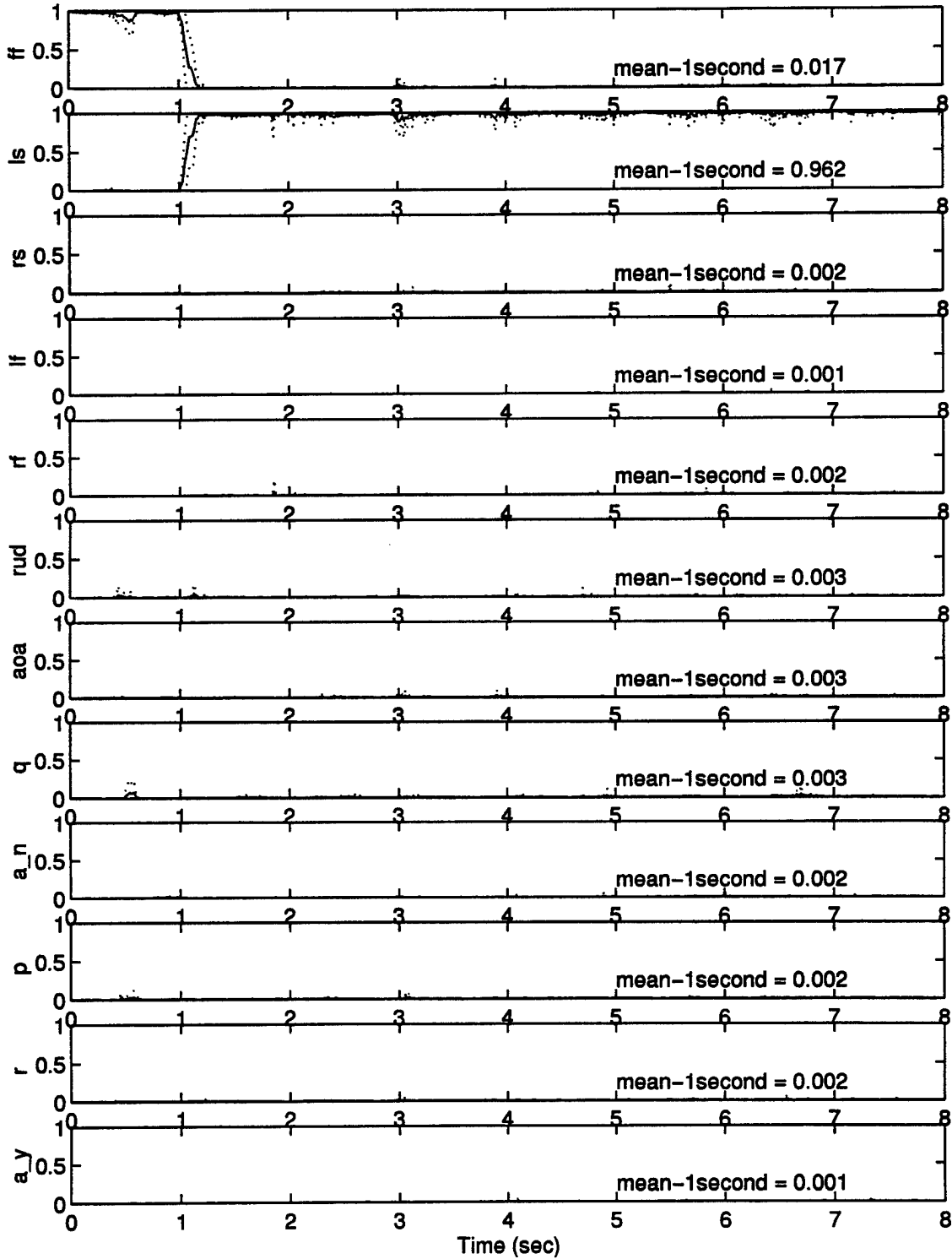
Summary Plot (with Mean +/- Sigma) for curt0: 10 runs



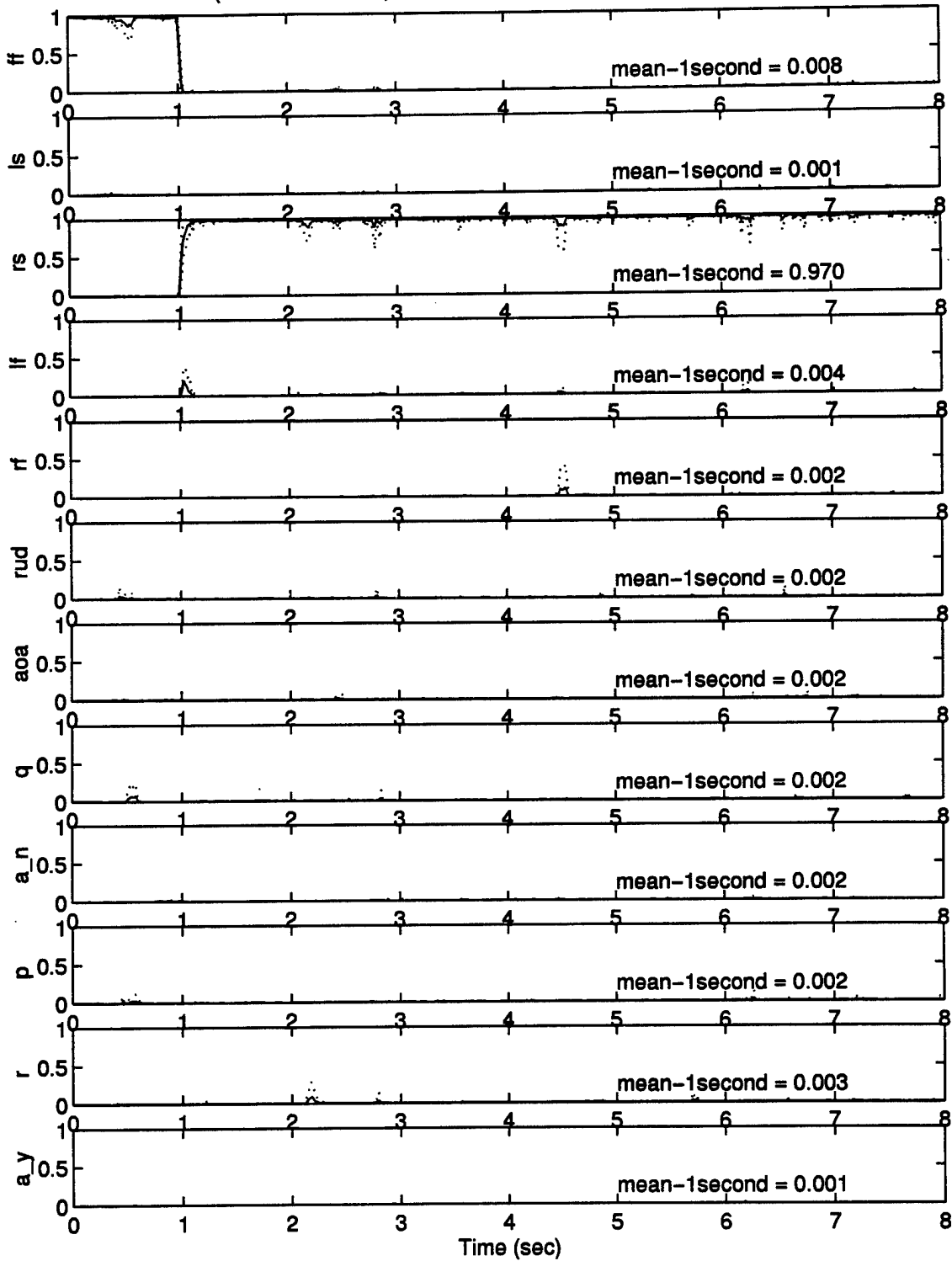
Mean (+/- One Std Dev) Probabilities of Fully Functional Aircraft: 10 runs



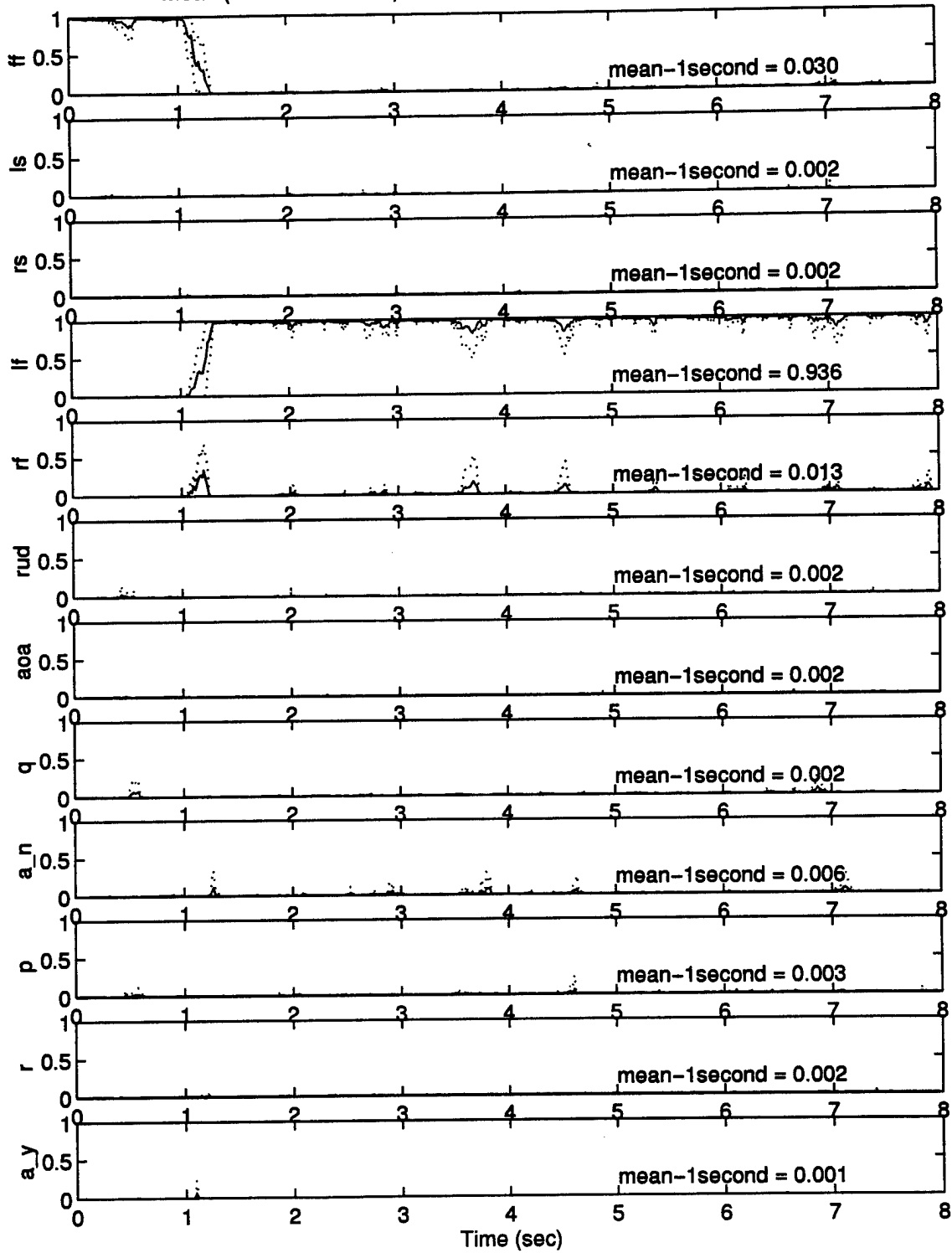
Mean (+/- One Std Dev) Probabilities of Left Stabilator Failure: 10 runs



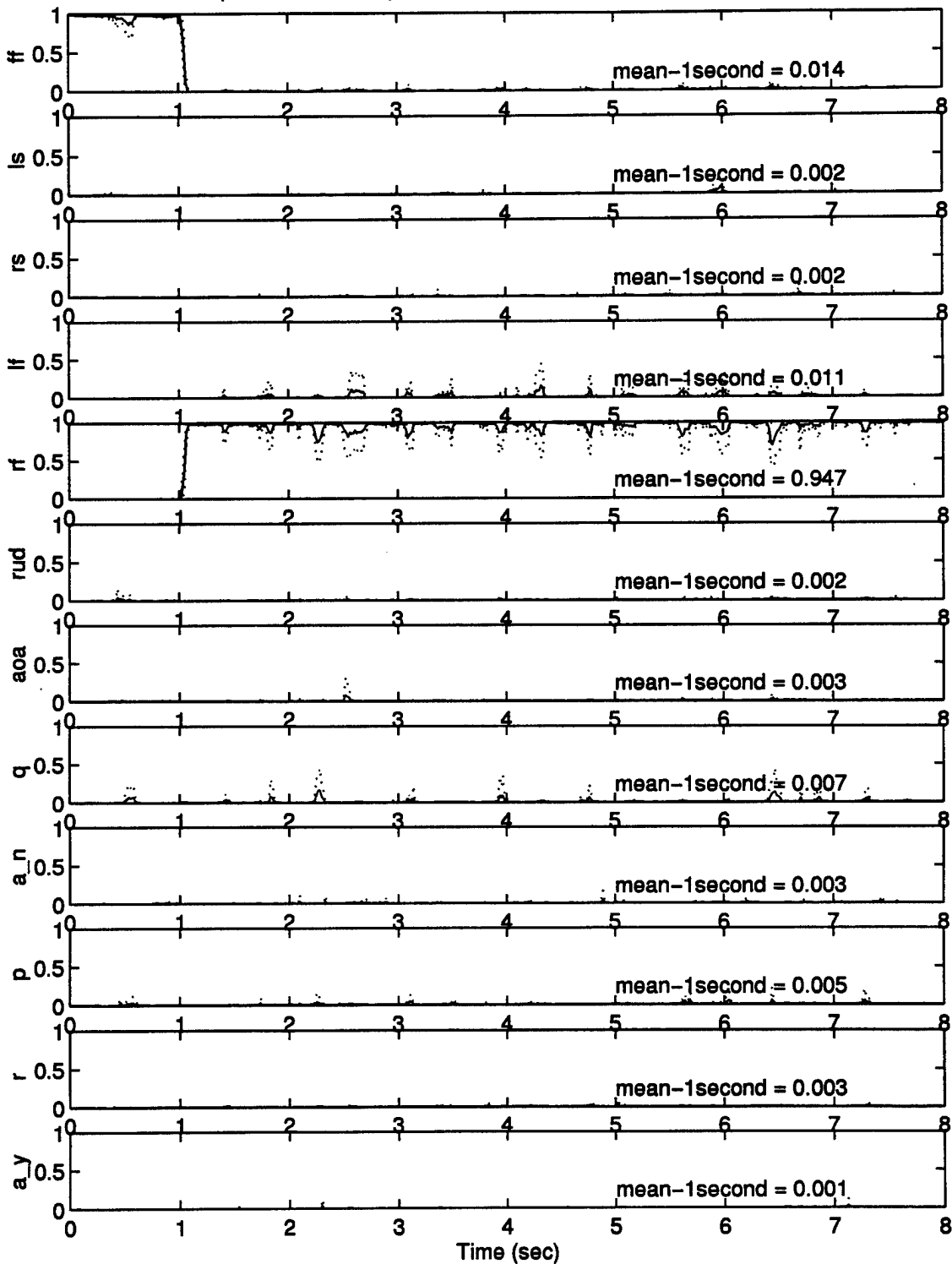
Mean (+/- One Std Dev) Probabilities of Right Stabilator Failure: 10 runs



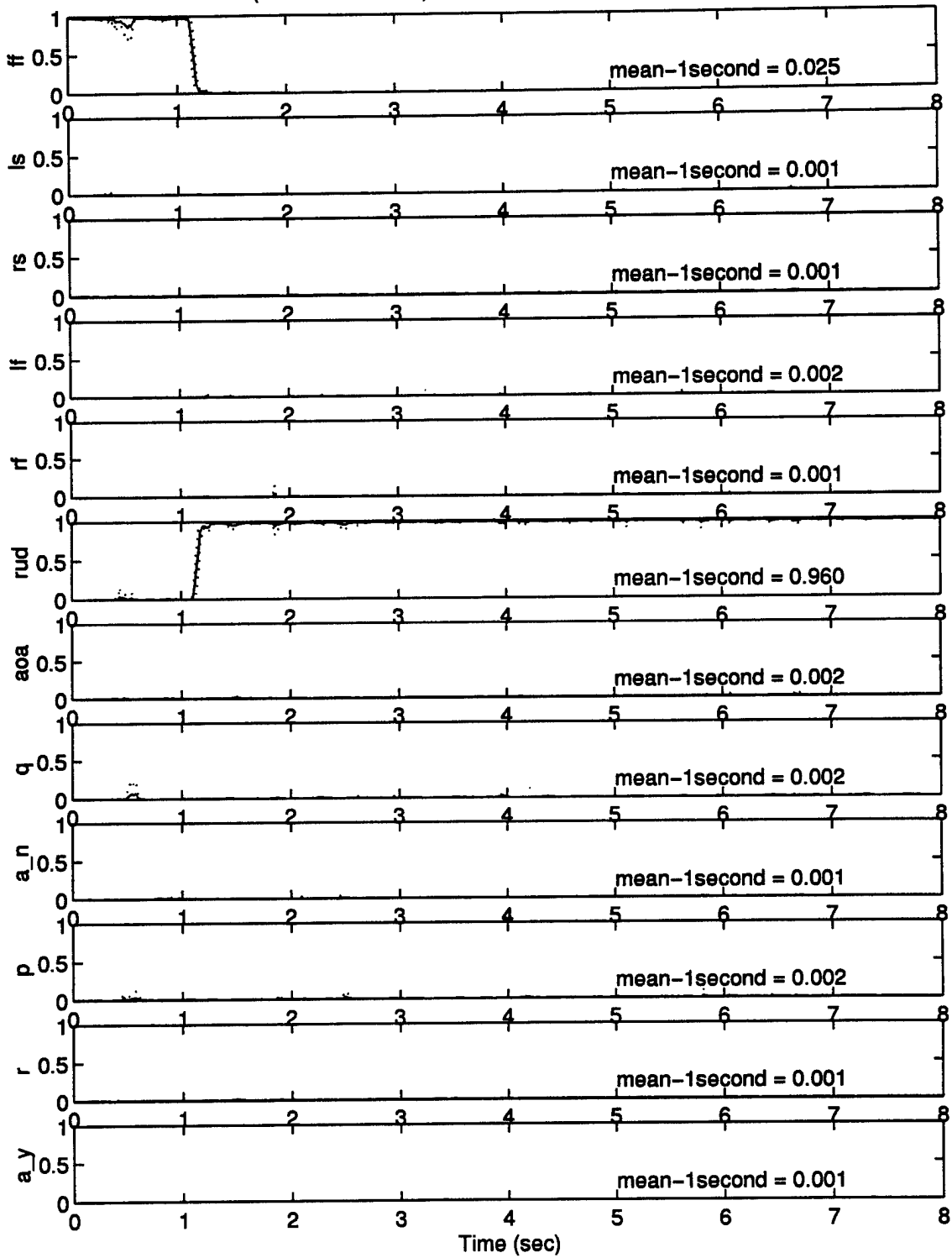
Mean (+/- One Std Dev) Probabilities of Left Flaperon Failure: 10 runs



Mean (+/- One Std Dev) Probabilities of Right Flaperon Failure: 10 runs



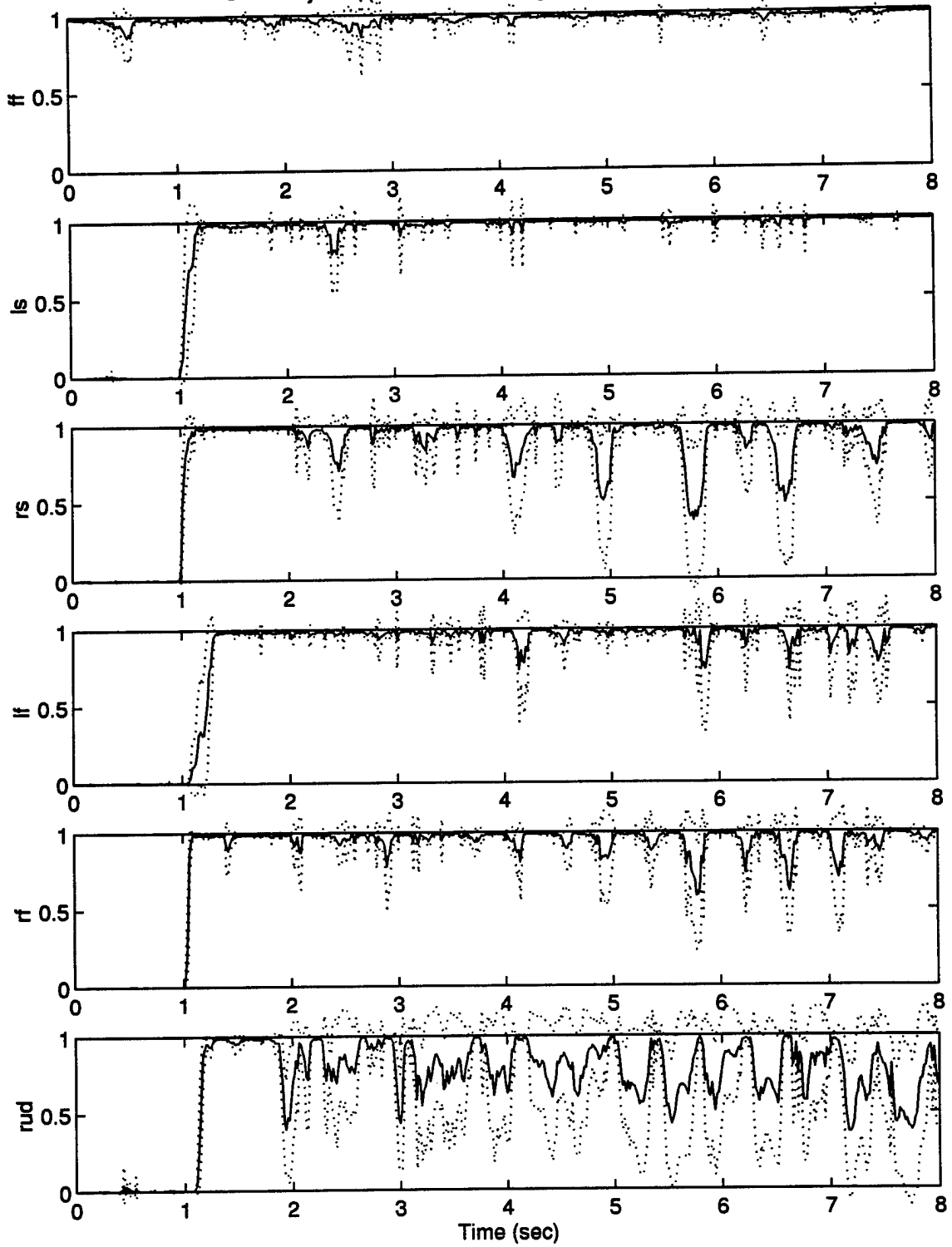
Mean (+/- One Std Dev) Probabilities of Rudder Failure: 10 runs



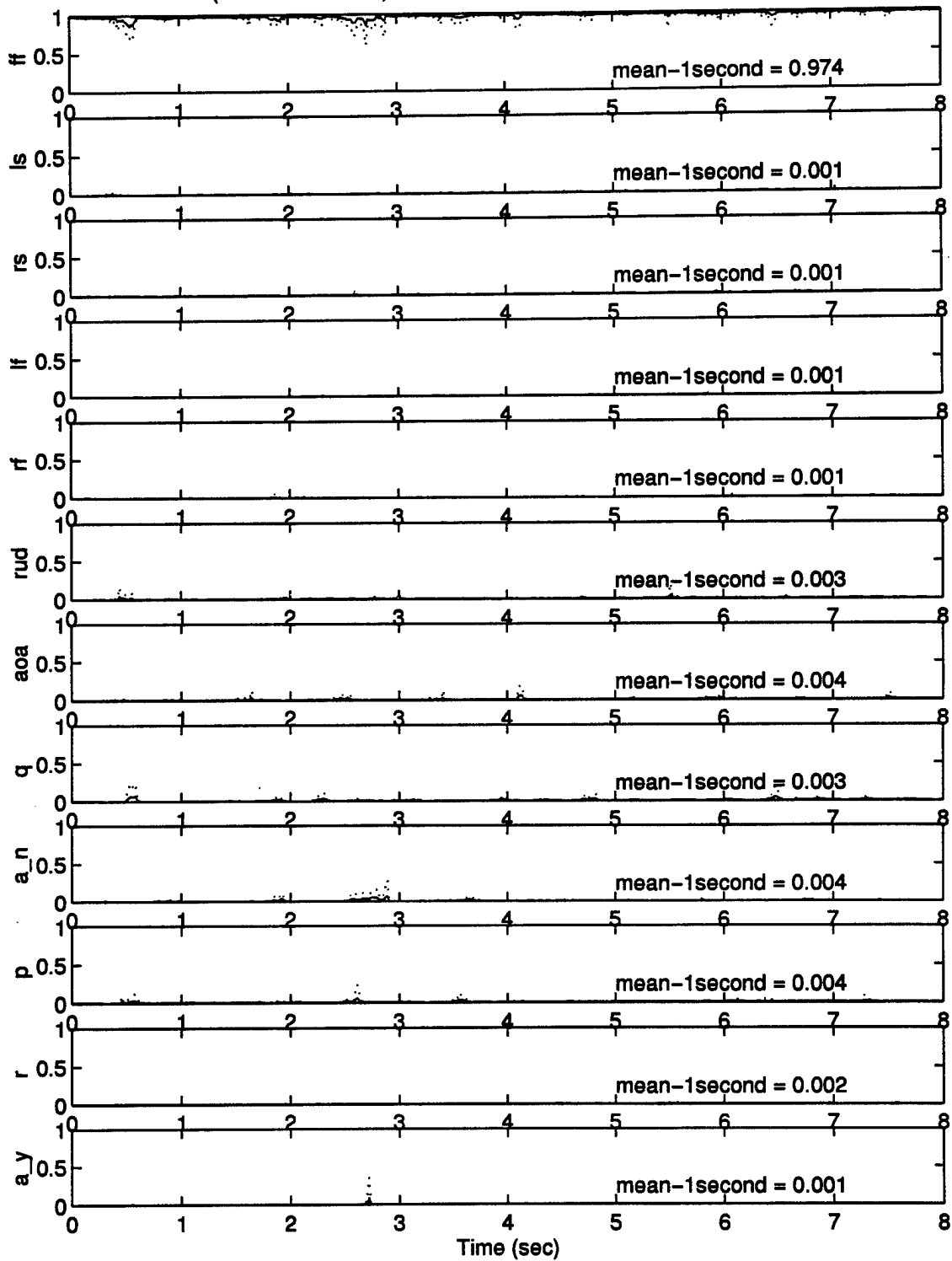
*Appendix A.2: Single Total Actuator Impairments ($\varepsilon = 0$), Control Redistribution 'ON', Dither
'ON', No Maneuvers*

This appendix contains the Probability Summary Plot and individual probability plots for cases of single, total (100%) actuator impairments, without aircraft maneuvering, but *with* Control Reconfiguration (Redistribution), and with control dithering (Section 4.11.2).

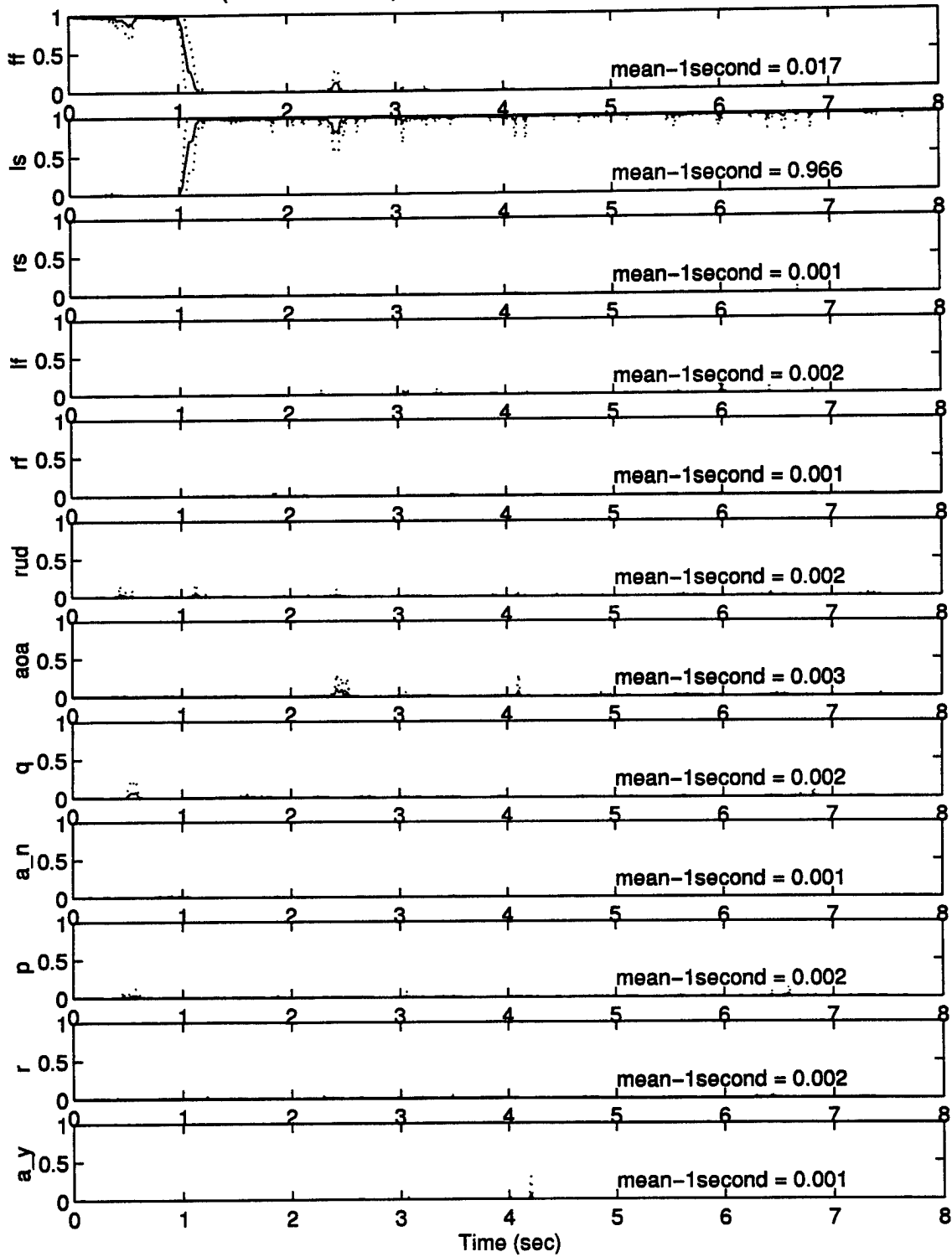
Summary Plot (with Mean \pm Sigma) for recon0: 10 runs



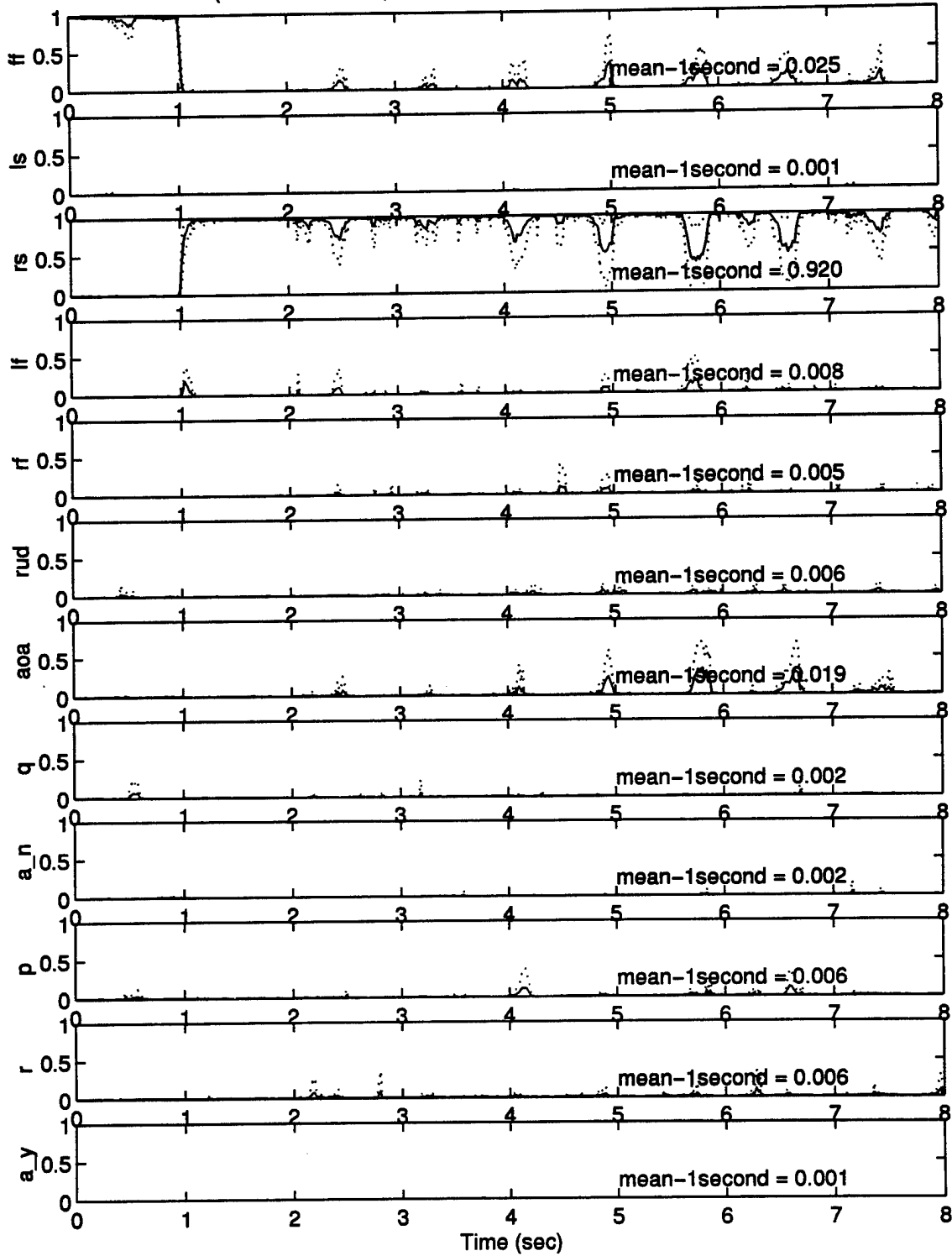
Mean (+/- One Std Dev) Probabilities of Fully Functional Aircraft: 10 runs



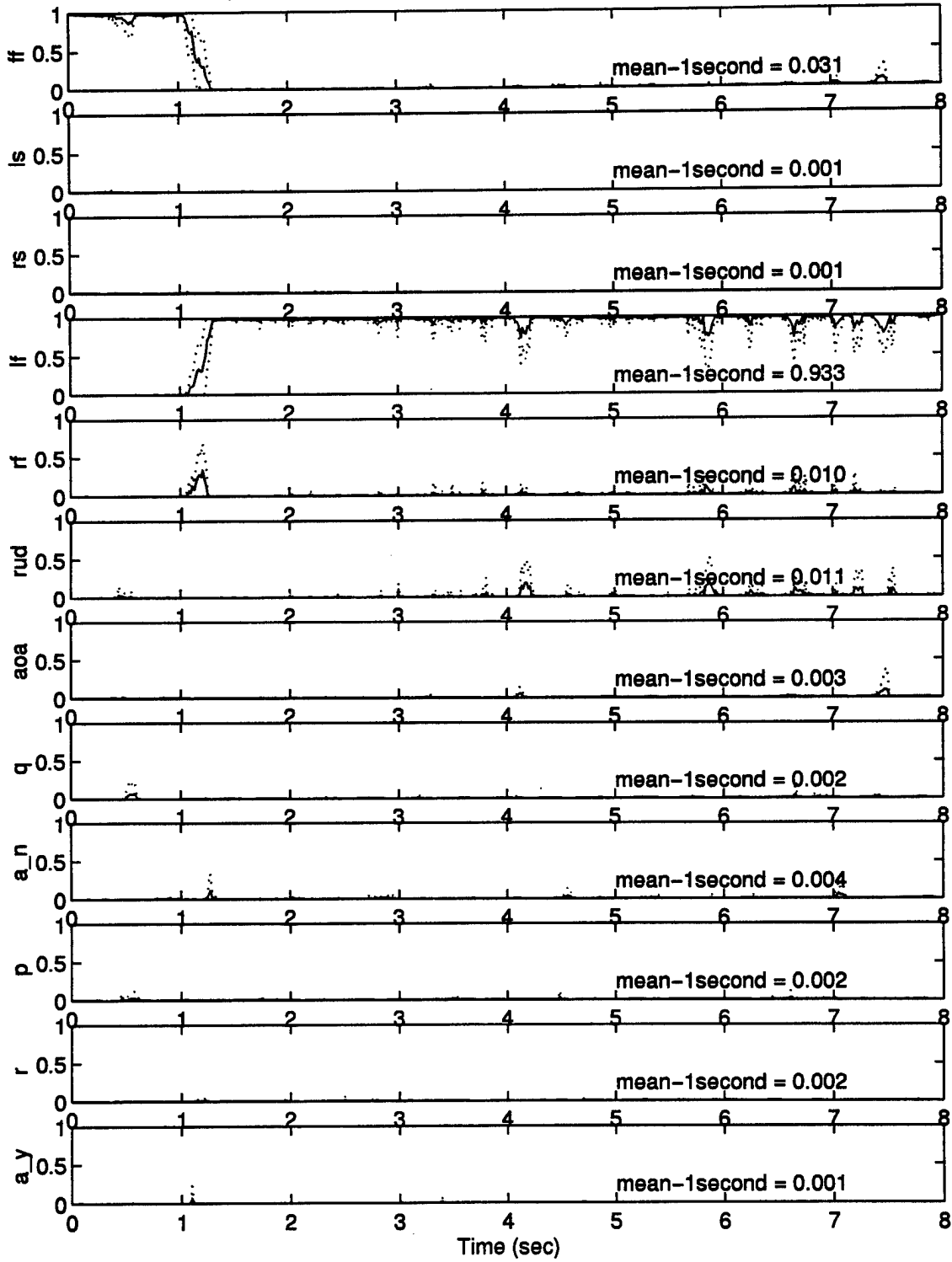
Mean (+/- One Std Dev) Probabilities of Left Stabilator Failure: 10 runs



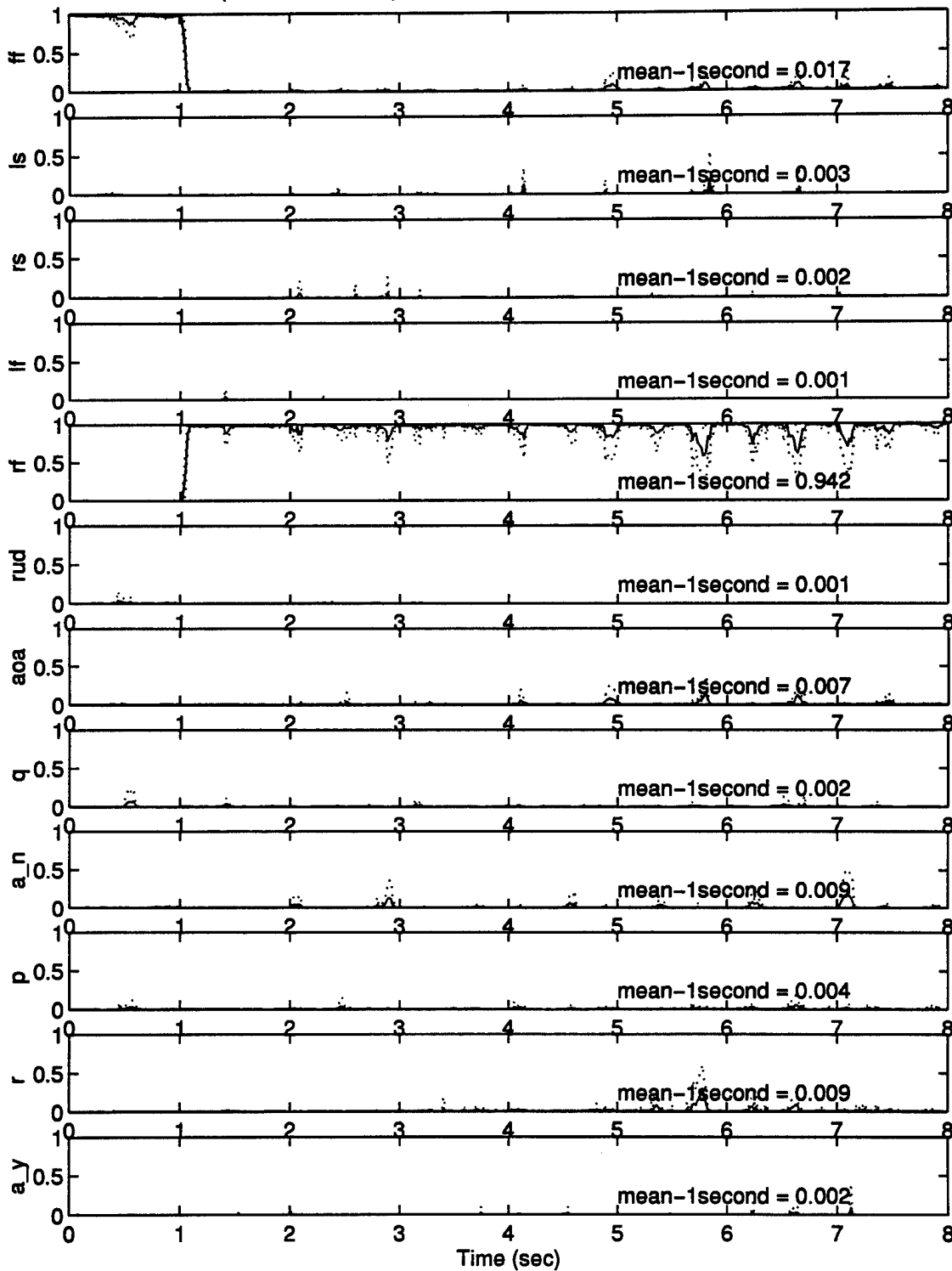
Mean (+/- One Std Dev) Probabilities of Right Stabilator Failure: 10 runs



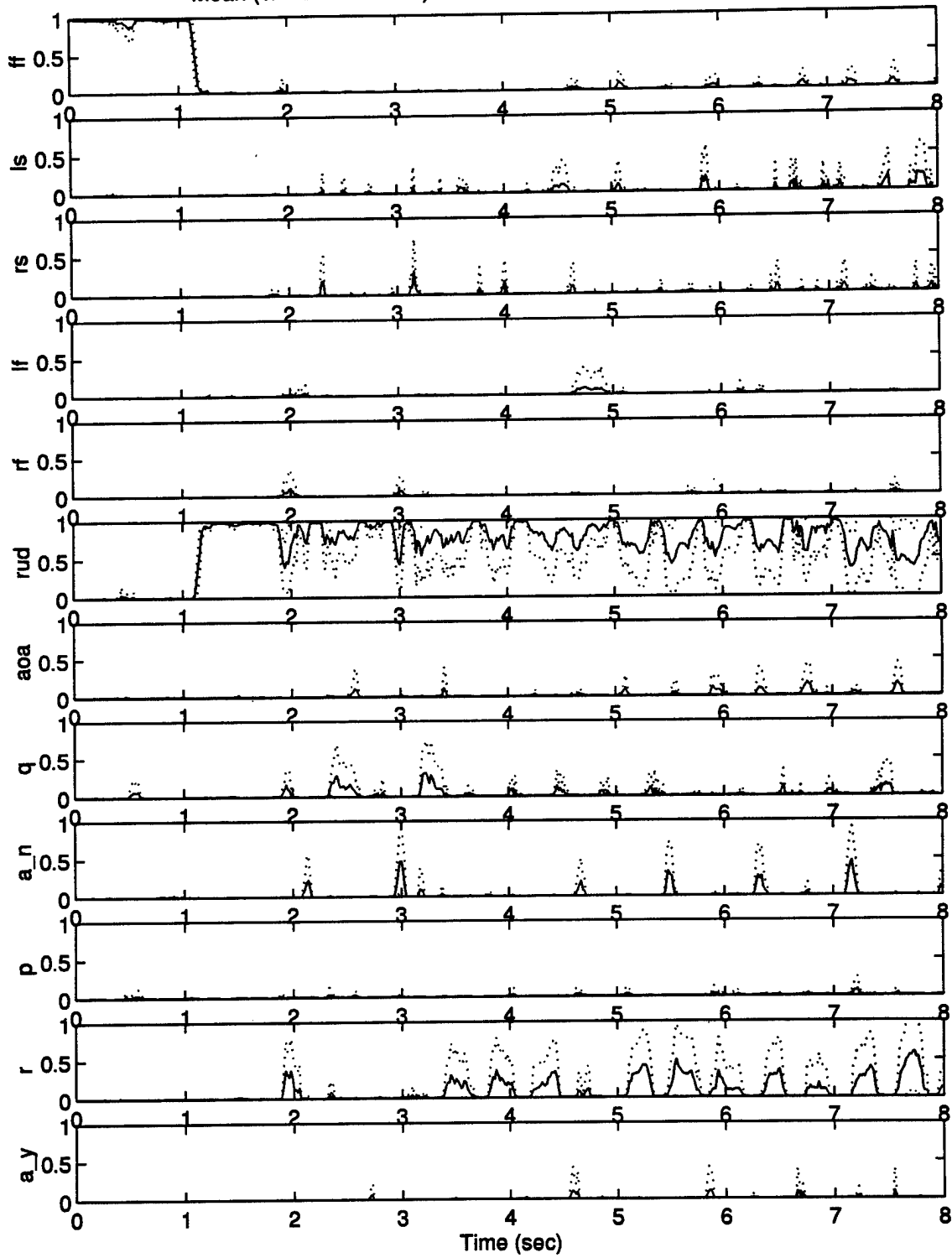
Mean (+/- One Std Dev) Probabilities of Left Flaperon Failure: 10 runs



Mean (+/- One Std Dev) Probabilities of Right Flaperon Failure: 10 runs



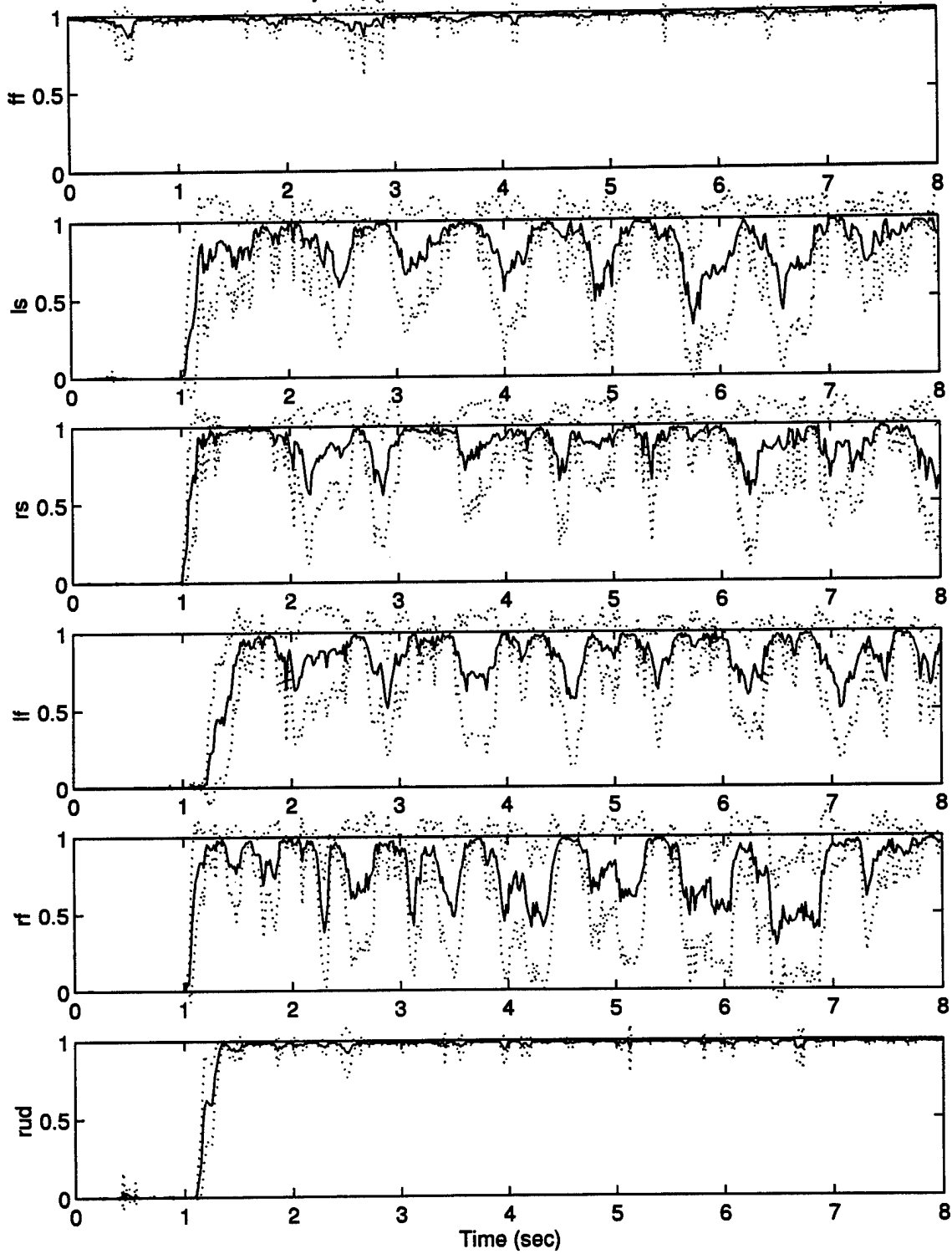
Mean (+/- One Std Dev) Probabilities of Rudder Failure: 10 runs



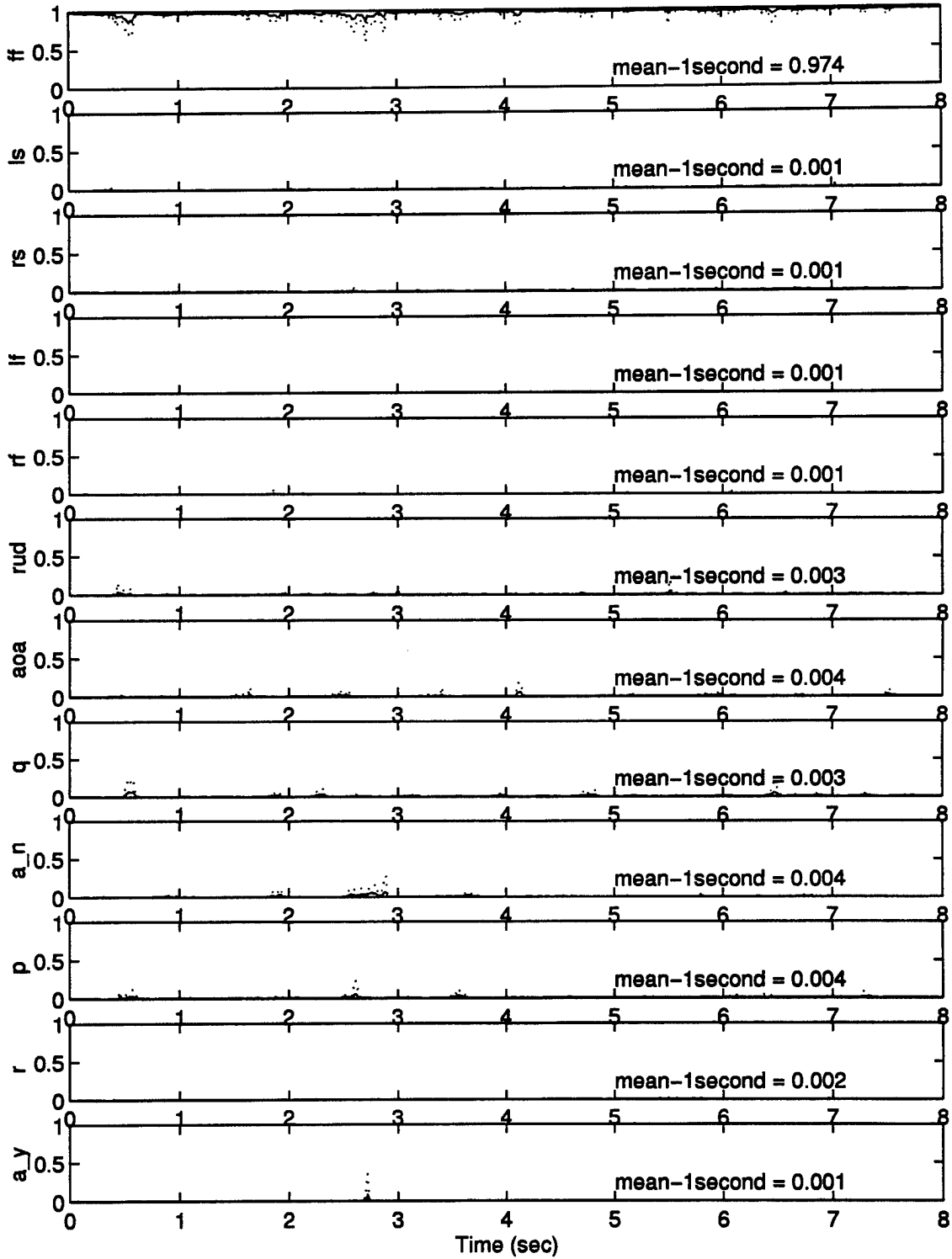
*Appendix B.1: Single 75% Actuator Impairments ($\epsilon = .25$), Control Redistribution 'OFF', Dither
'ON', No Maneuvers*

This appendix contains the Probability Summary Plot and individual probability plots for cases of single, 75% ($\epsilon = .25$) actuator impairments, without aircraft maneuvering or Control Reconfiguration (Redistribution), but with control dithering (Section 4.12.1).

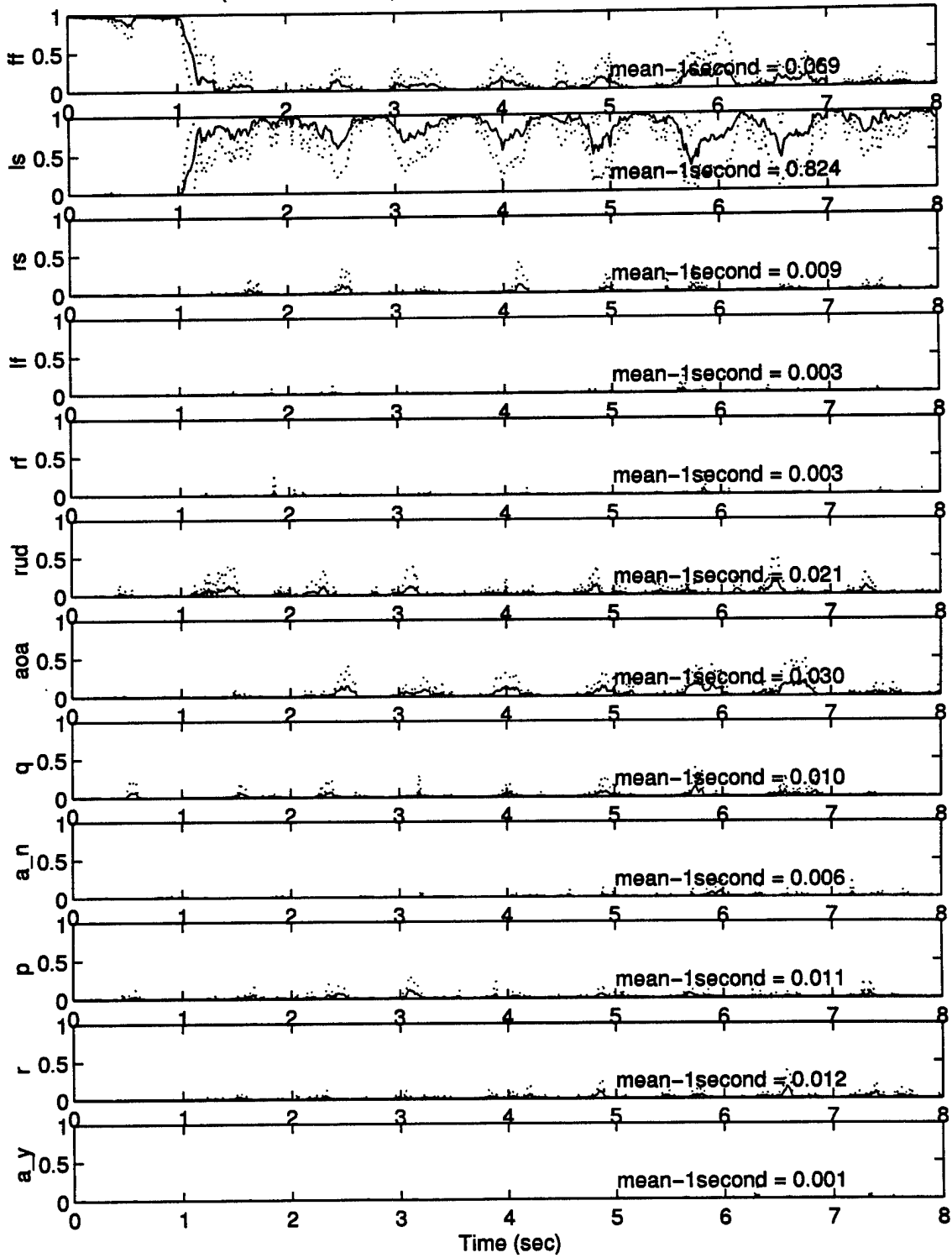
Summary Plot (with Mean \pm Sigma) for curt25: 10 runs



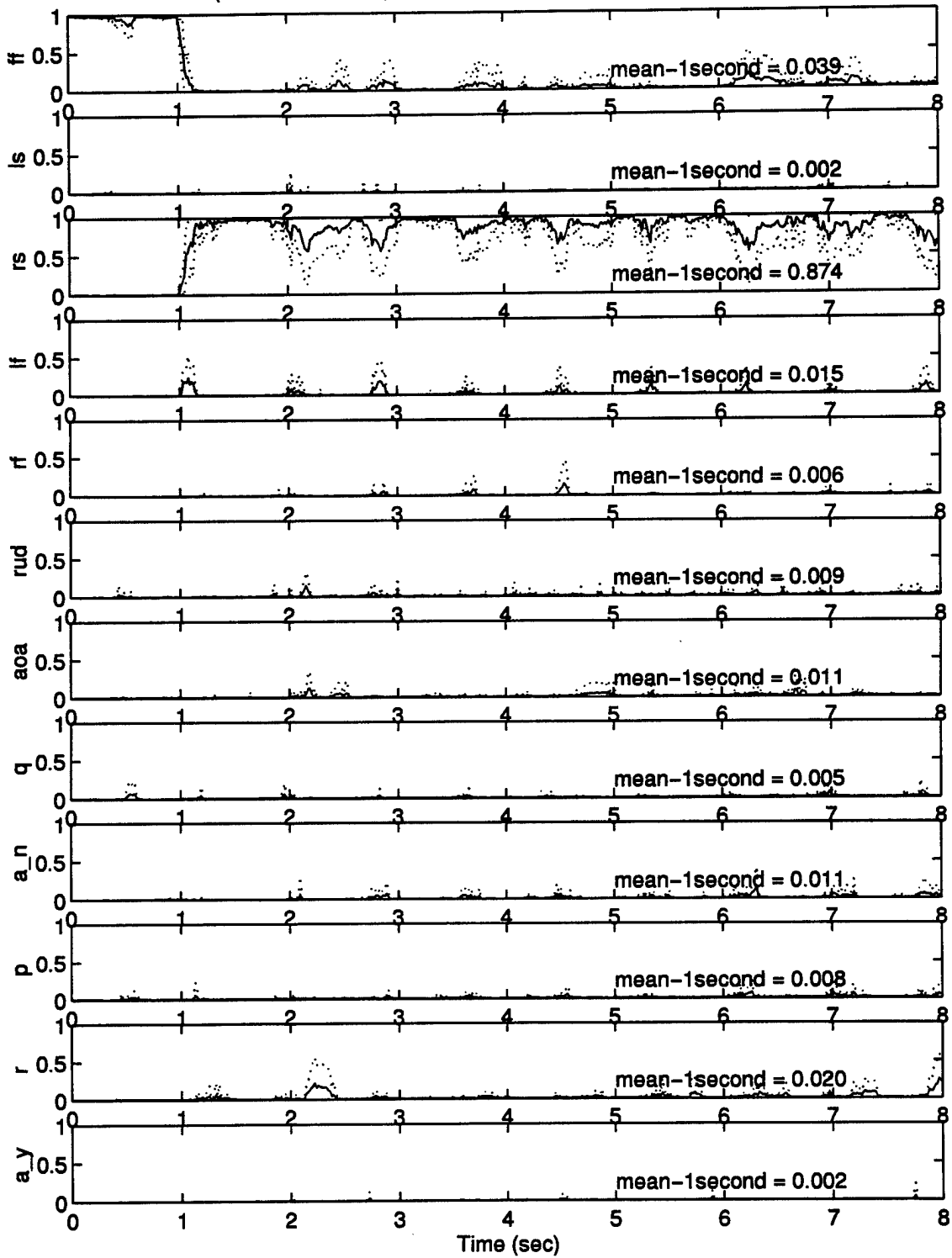
Mean (+/- One Std Dev) Probabilities of Fully Functional Aircraft: 10 runs



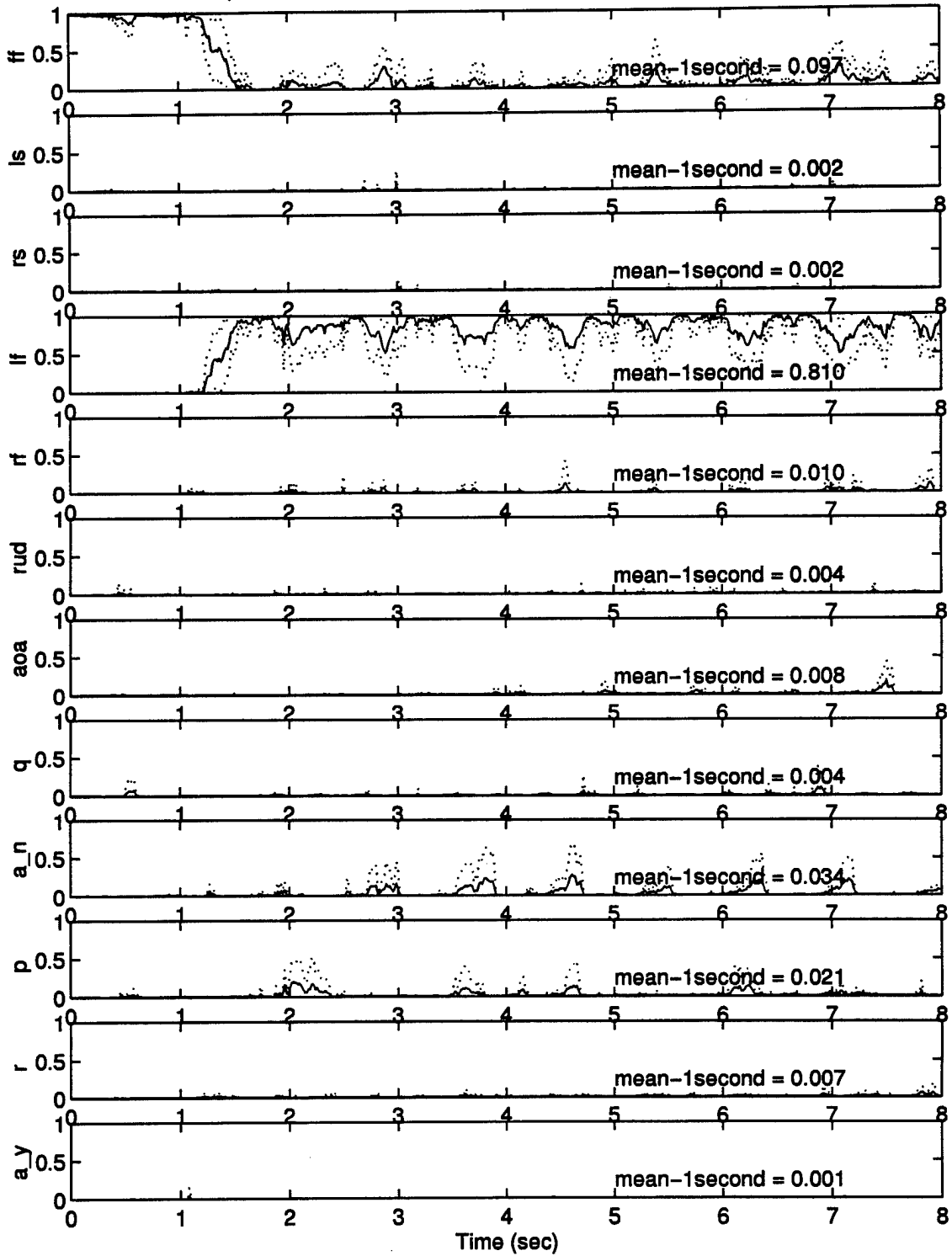
Mean (+/- One Std Dev) Probabilities of Left Stabilator Failure: 10 runs



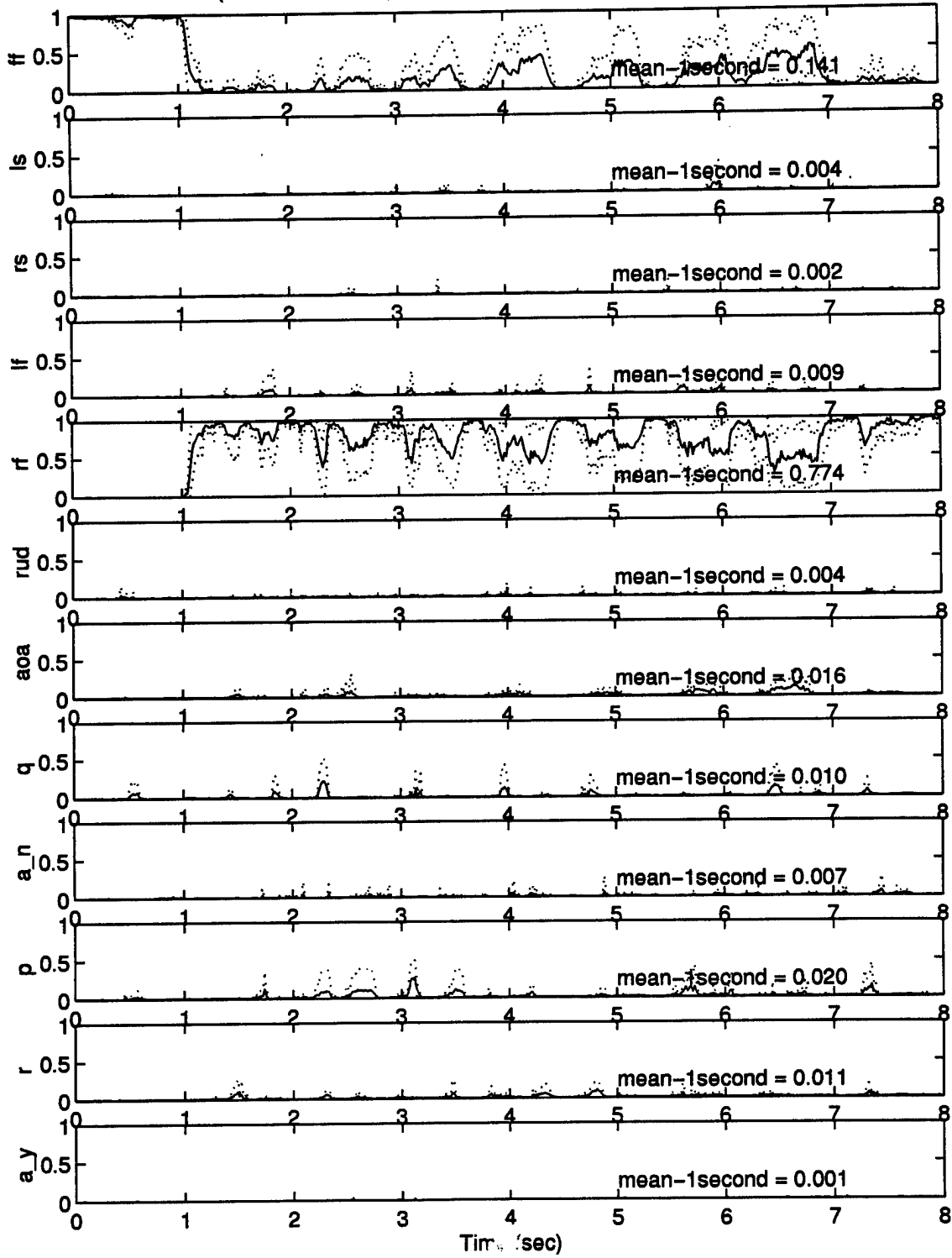
Mean (+/- One Std Dev) Probabilities of Right Stabilator Failure: 10 runs



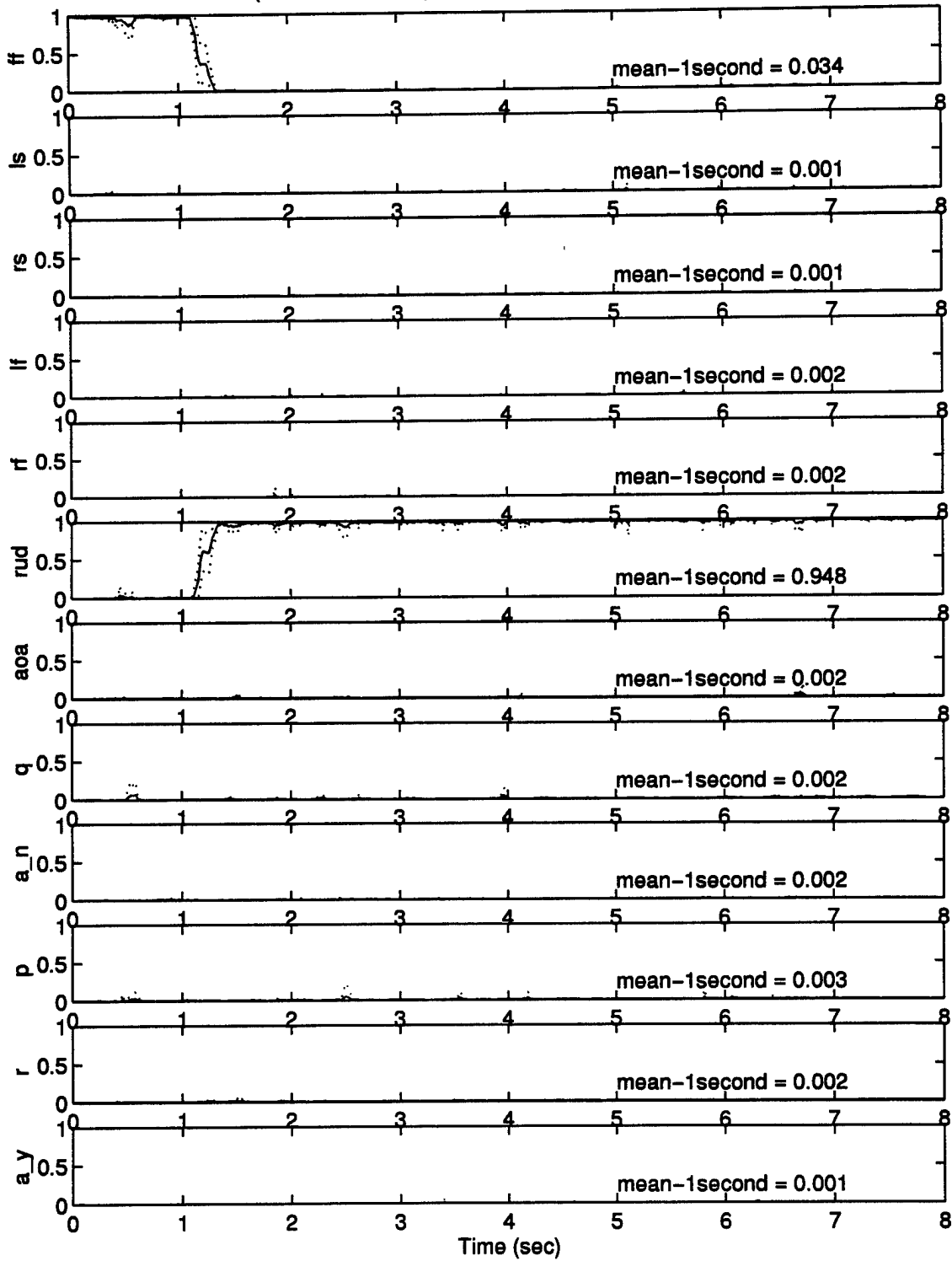
Mean (+/- One Std Dev) Probabilities of Left Flaperon Failure: 10 runs



Mean (+/- One Std Dev) Probabilities of Right Flaperon Failure: 10 runs



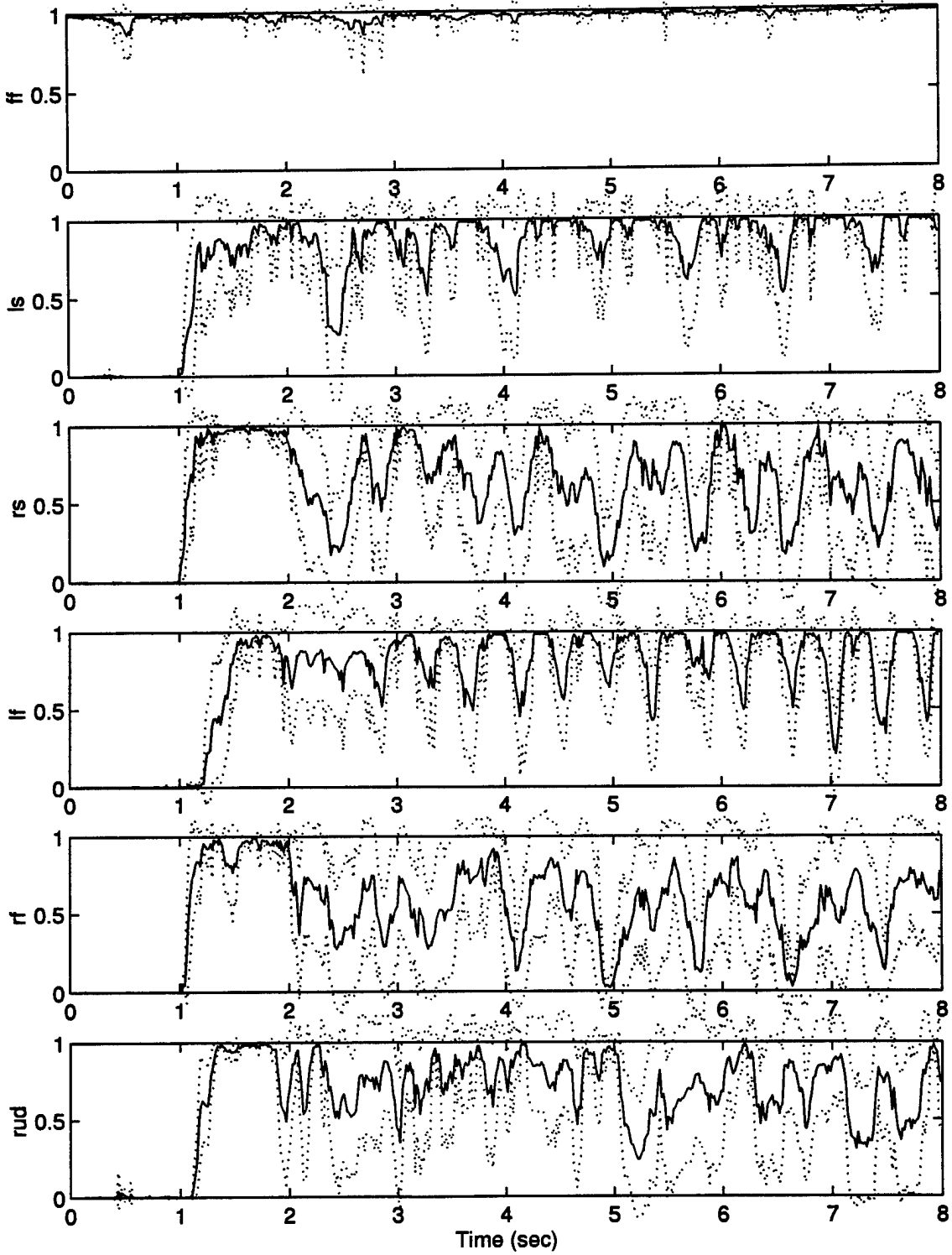
Mean (+/- One Std Dev) Probabilities of Rudder Failure: 10 runs



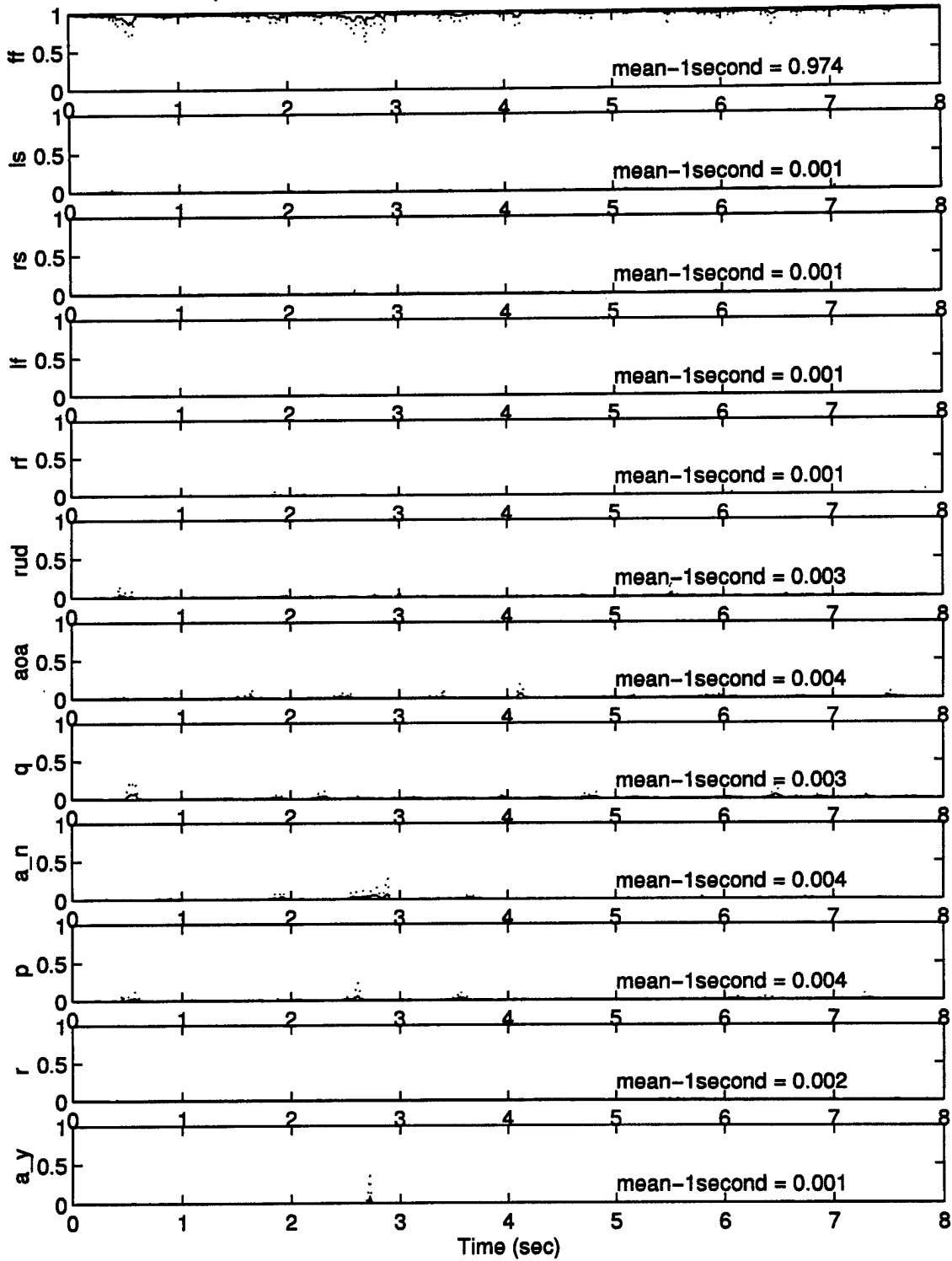
*Appendix B.2: Single 75% Actuator Impairments ($\epsilon = .25$), Control Redistribution 'ON', Dither
'ON', No Maneuvers*

This appendix contains the Probability Summary Plot and individual probability plots for cases of single, 75% ($\epsilon = .25$) actuator impairments, without aircraft maneuvering, but with Control Reconfiguration (Redistribution), and with control dithering (Section 4.12.2).

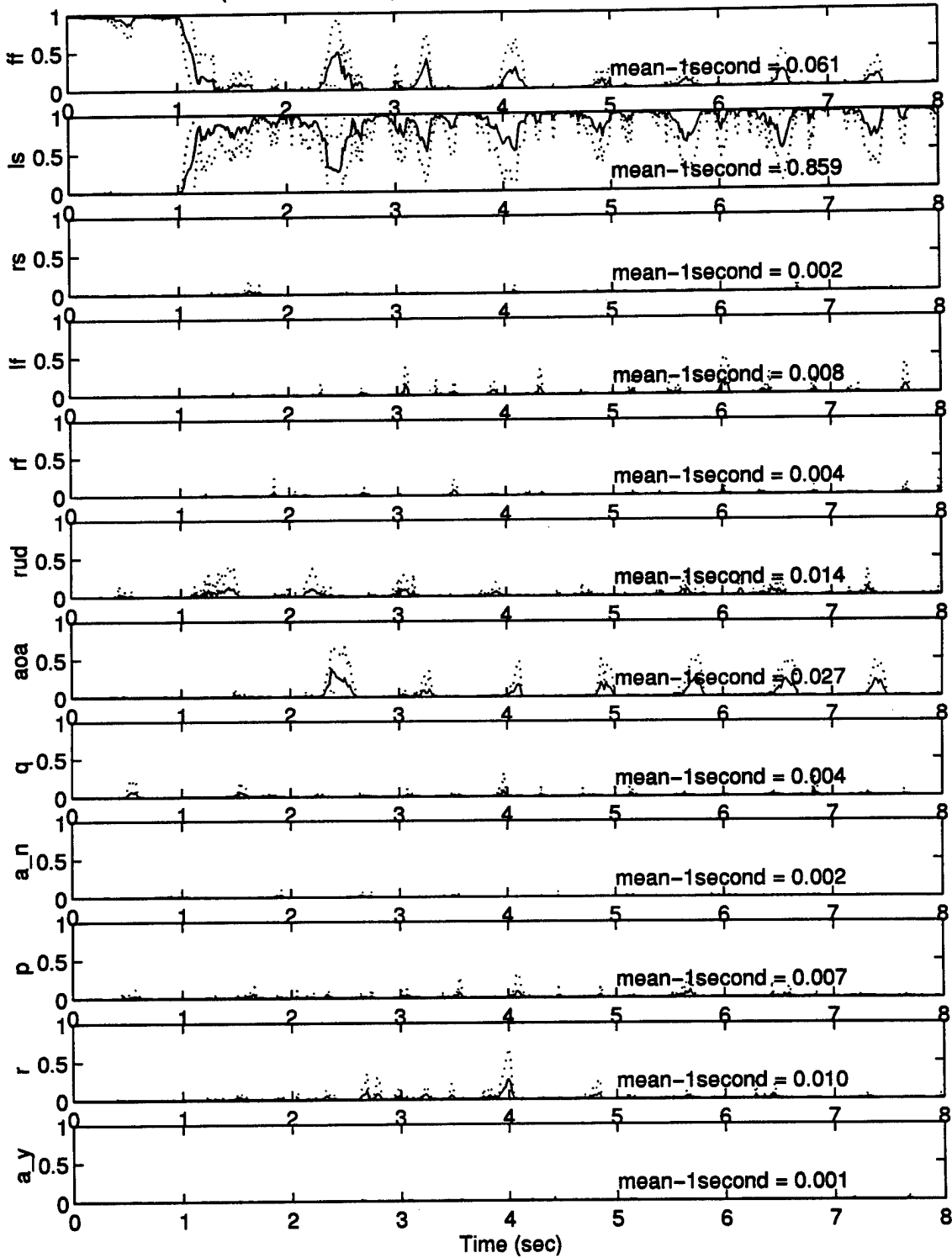
Summary Plot (with Mean \pm Sigma) for recon25: 10 runs



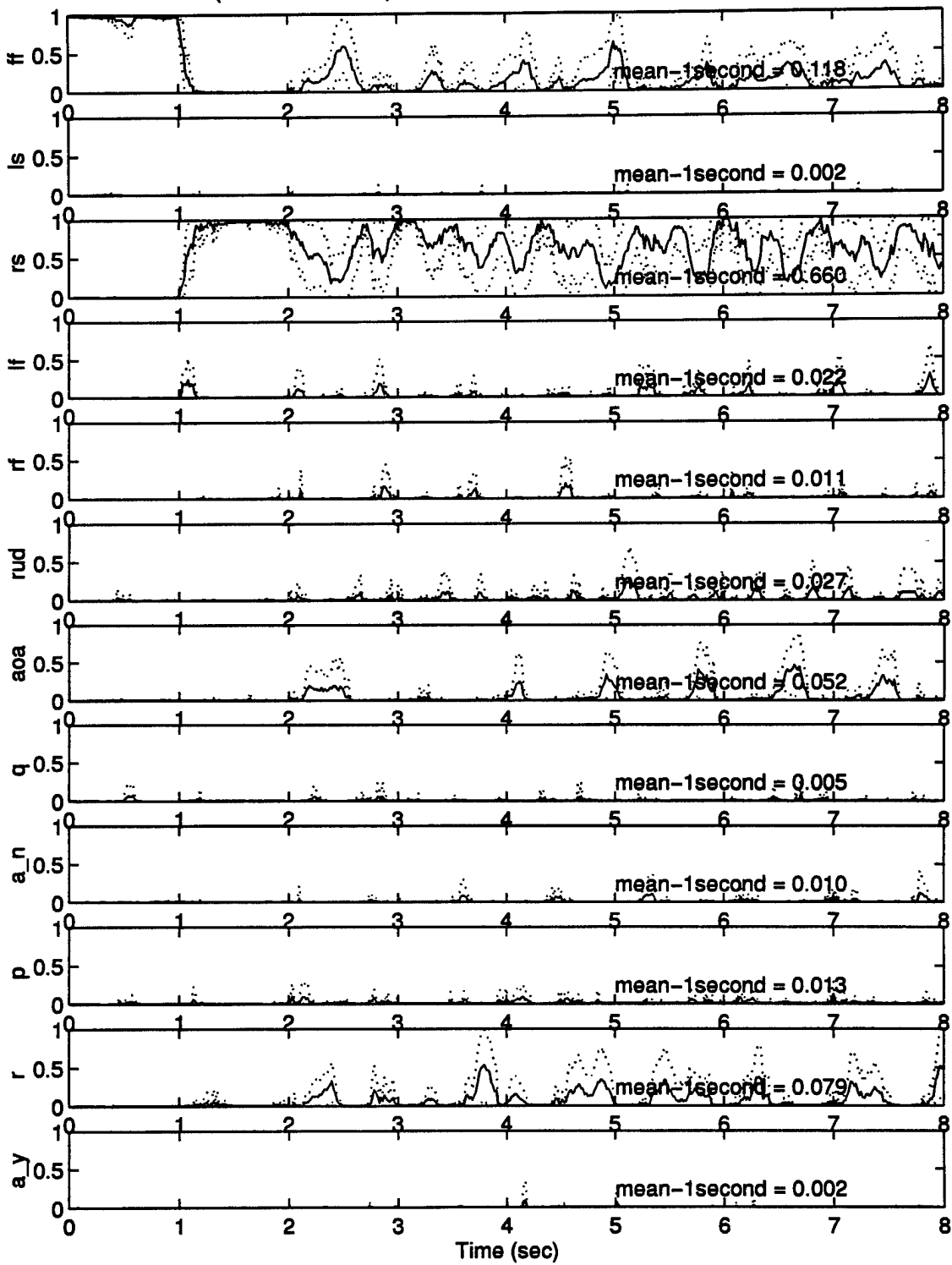
Mean (+/- One Std Dev) Probabilities of Fully Functional Aircraft: 10 runs



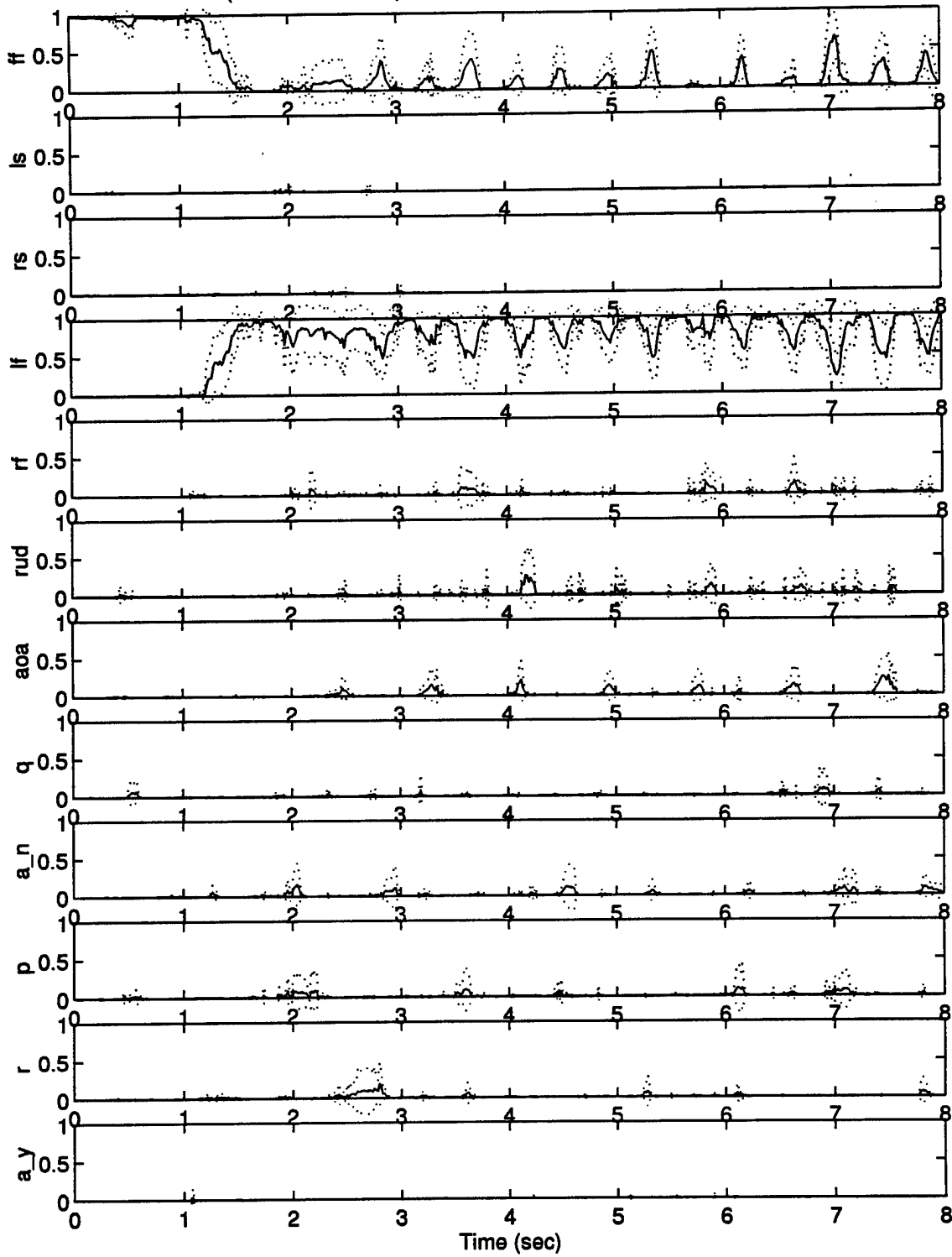
Mean (+/- One Std Dev) Probabilities of Left Stabilator Failure: 10 runs



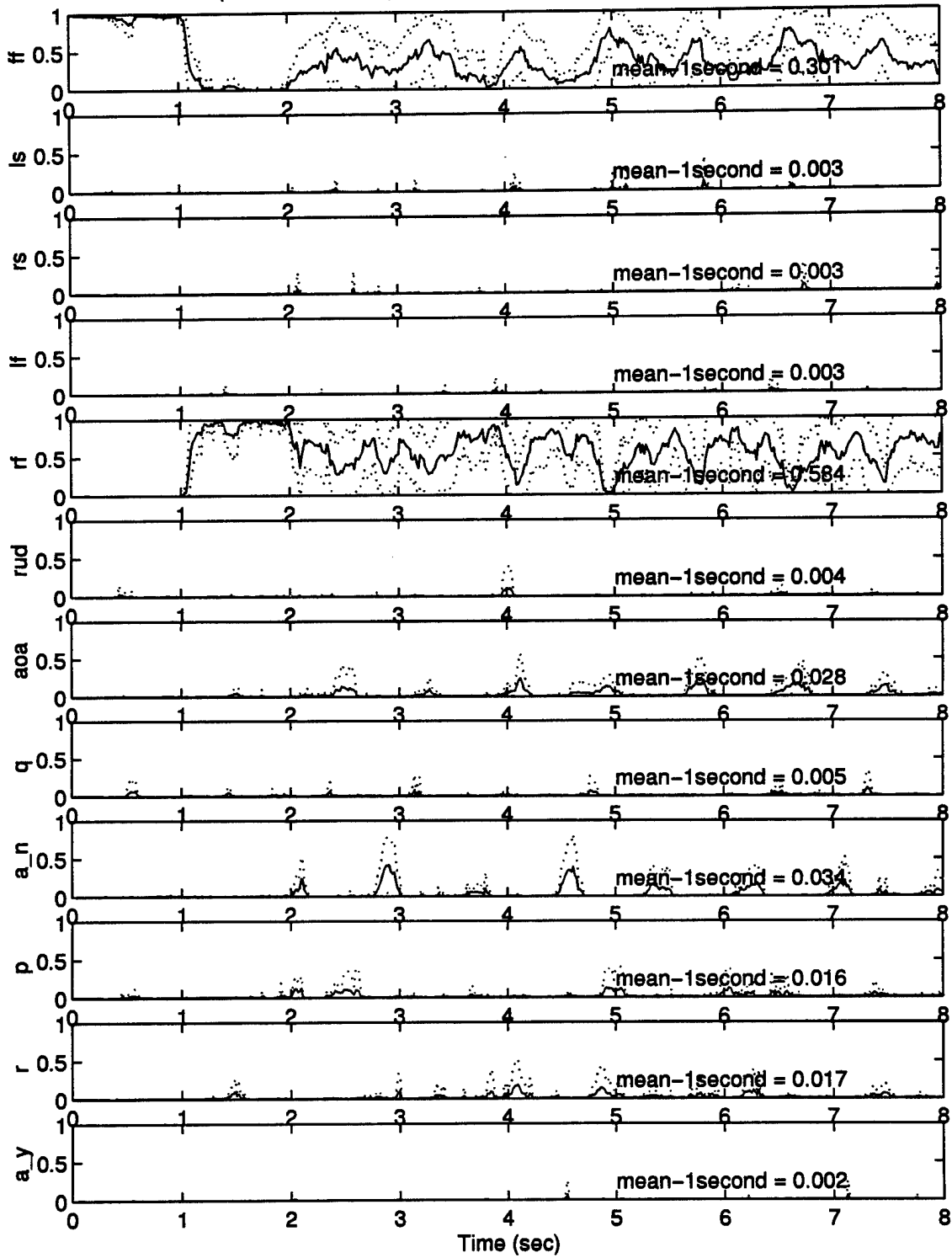
Mean (+/- One Std Dev) Probabilities of Right Stabilator Failure: 10 runs



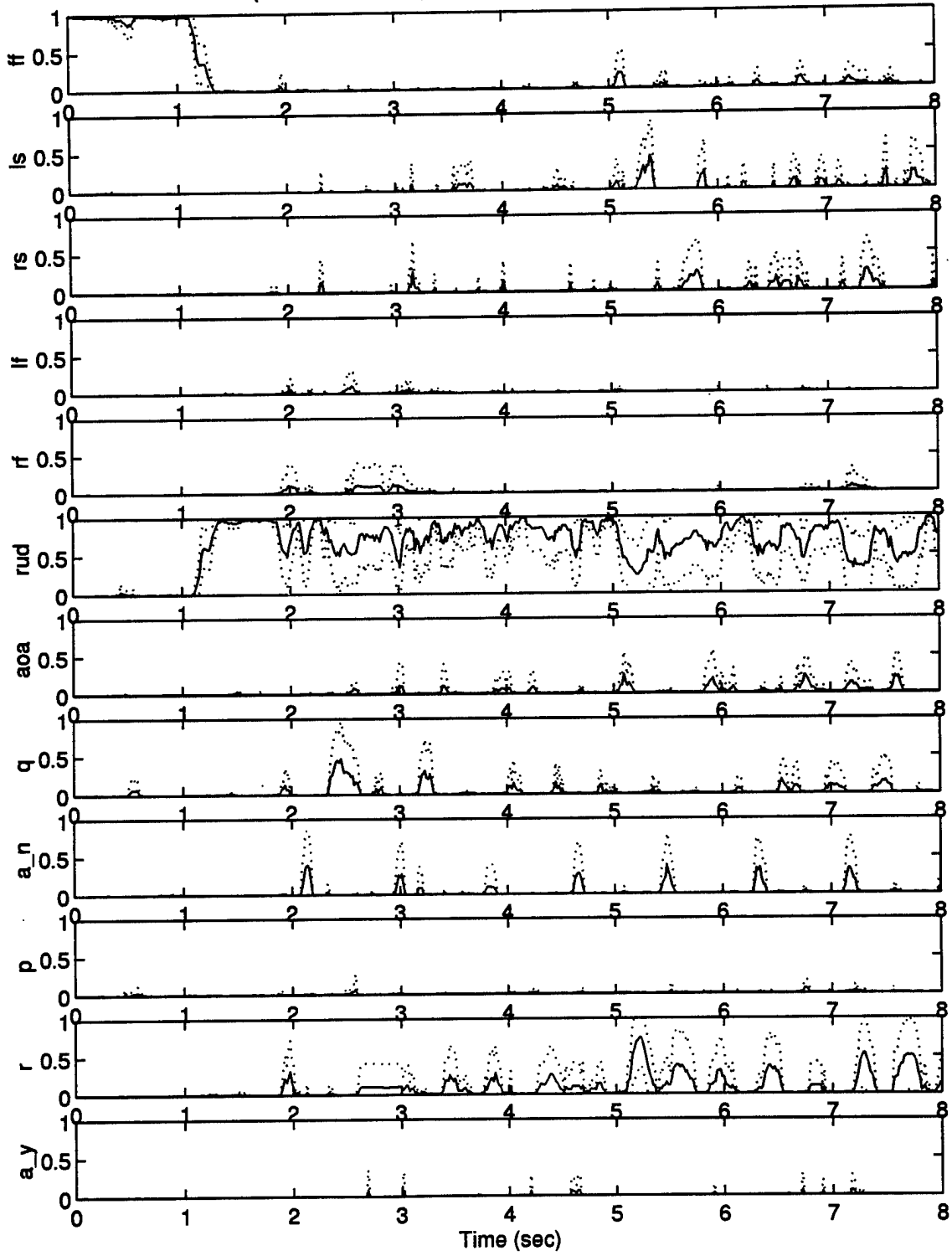
Mean (+/- One Std Dev) Probabilities of Left Flaperon Failure: 10 runs



Mean (+/- One Std Dev) Probabilities of Right Flaperon Failure: 10 runs



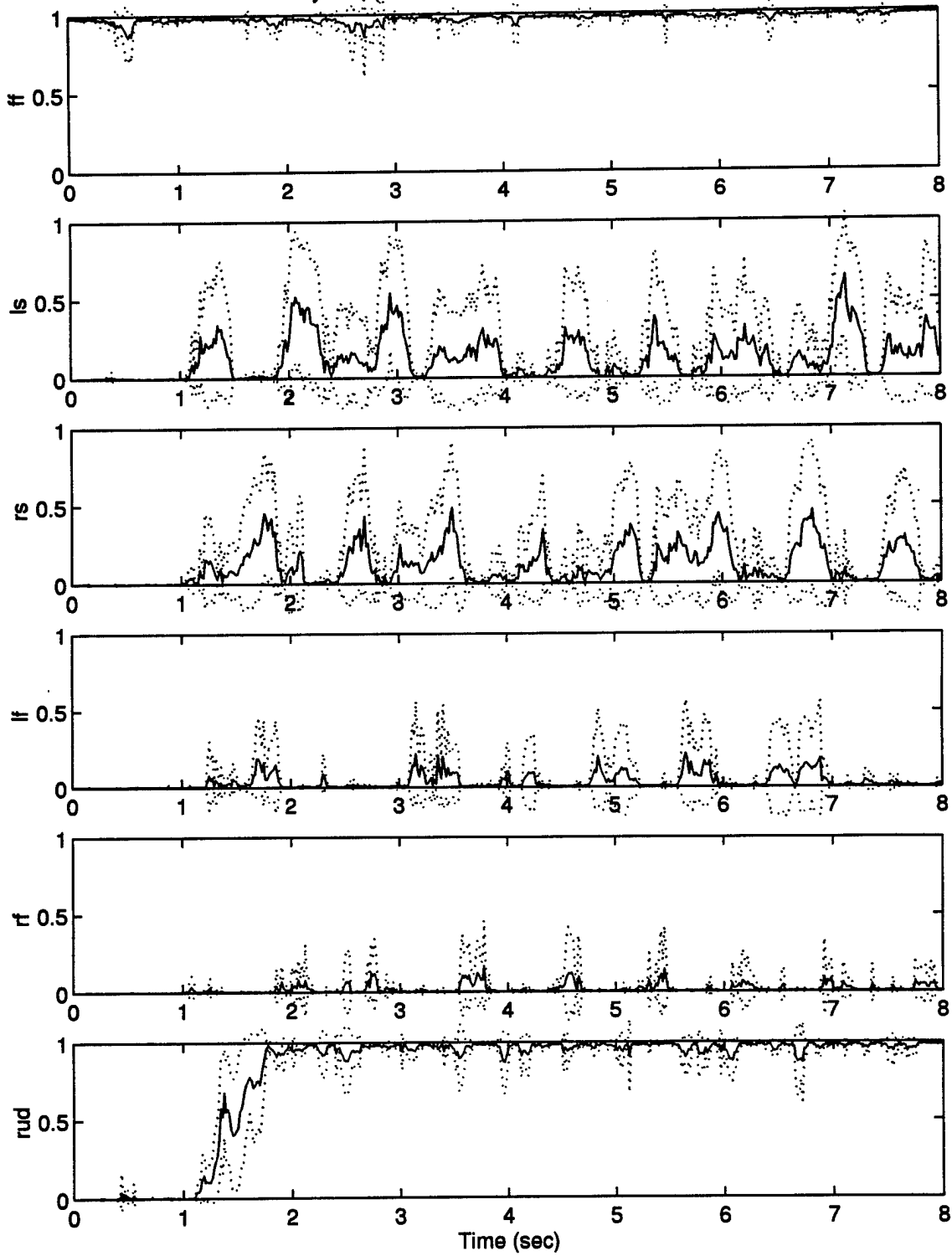
Mean (+/- One Std Dev) Probabilities of Rudder Failure: 10 runs



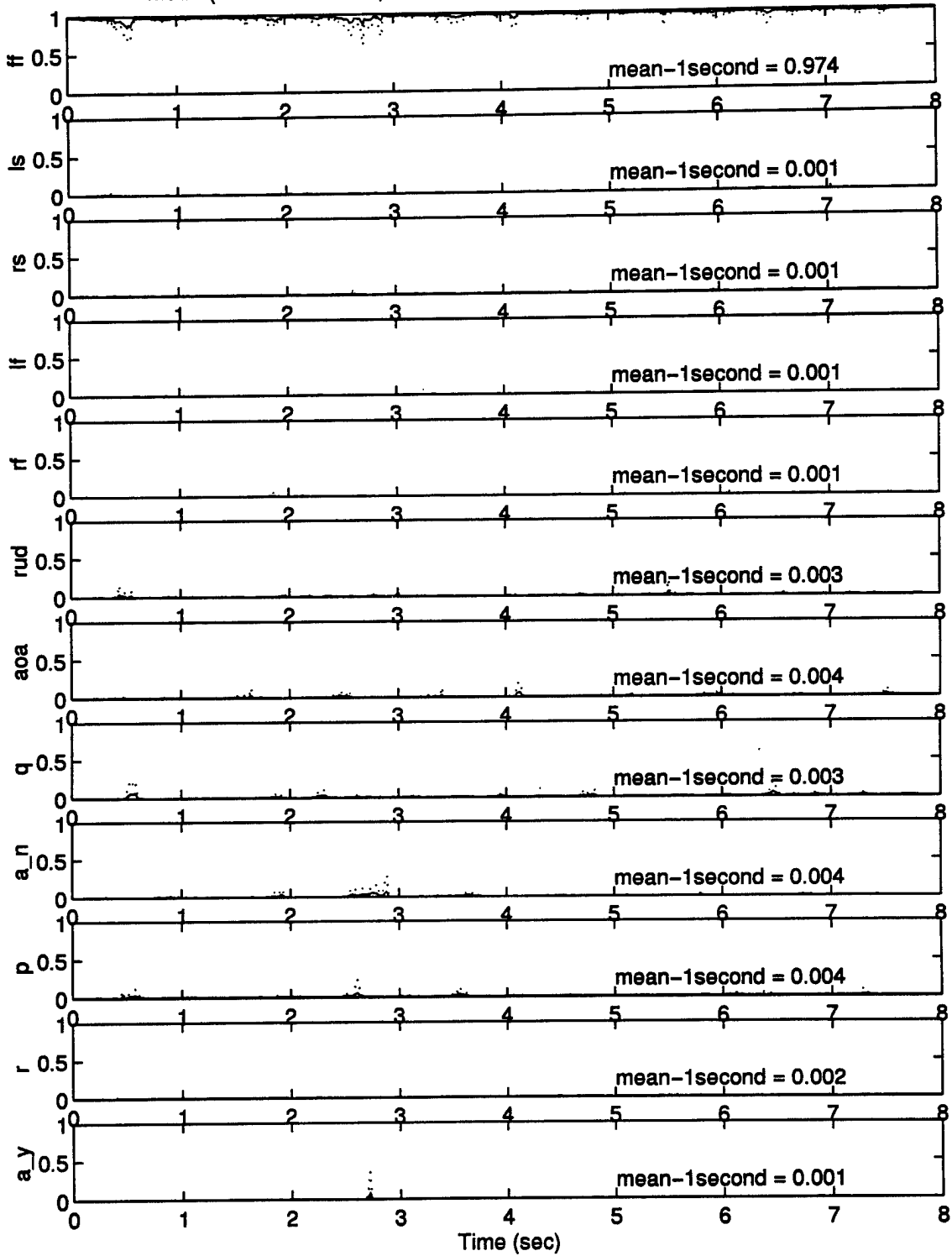
*Appendix C.1: Single 50% Actuator Impairments ($\epsilon = .5$), Control Redistribution 'OFF', Dither
'ON', No Maneuvers*

This appendix contains the Probability Summary Plot and individual probability plots for cases of single, 50% ($\epsilon = .5$) actuator impairments, without aircraft maneuvering or Control Reconfiguration (Redistribution), but with control dithering (Section 4.13.1).

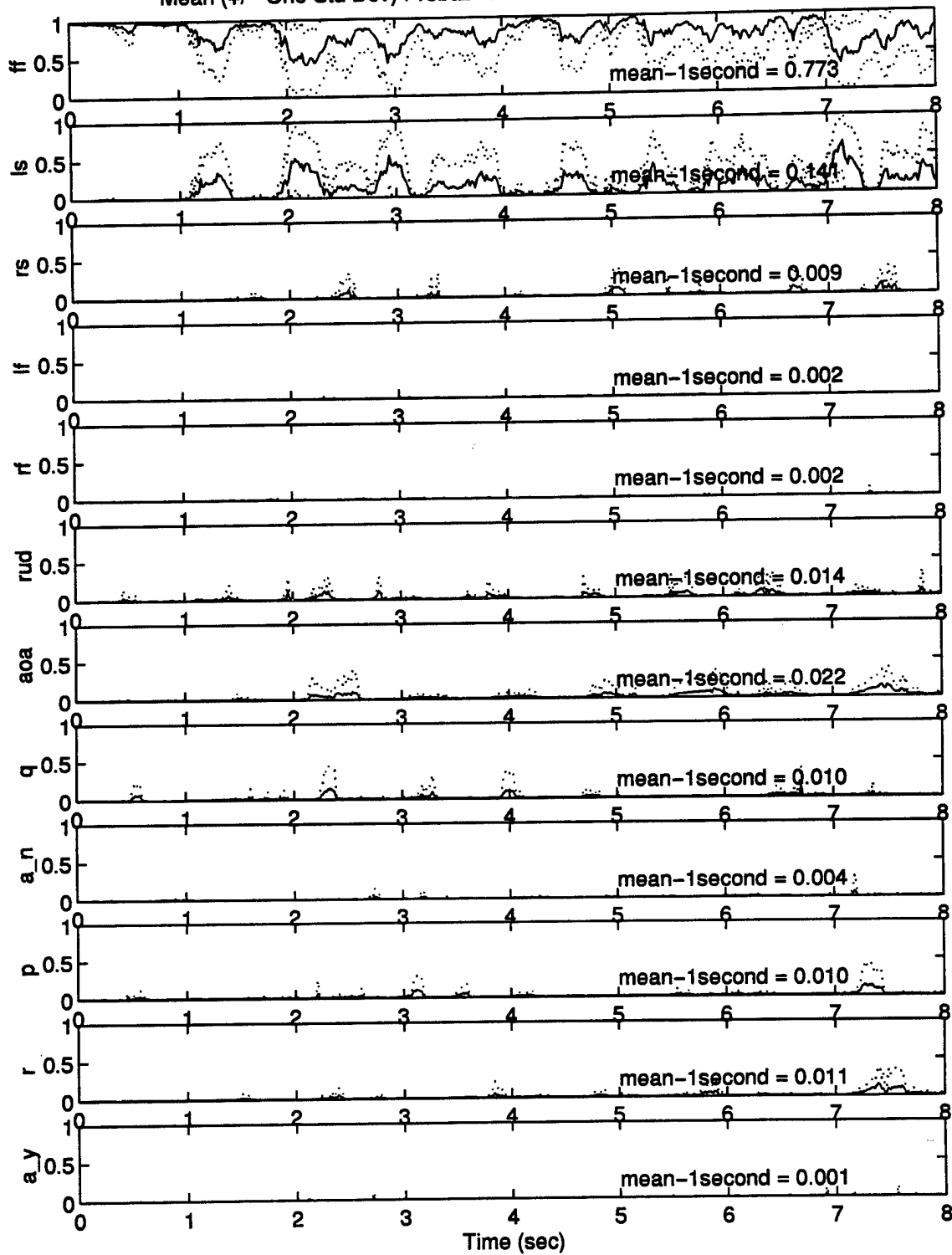
Summary Plot (with Mean \pm Sigma) for curt50: 10 runs



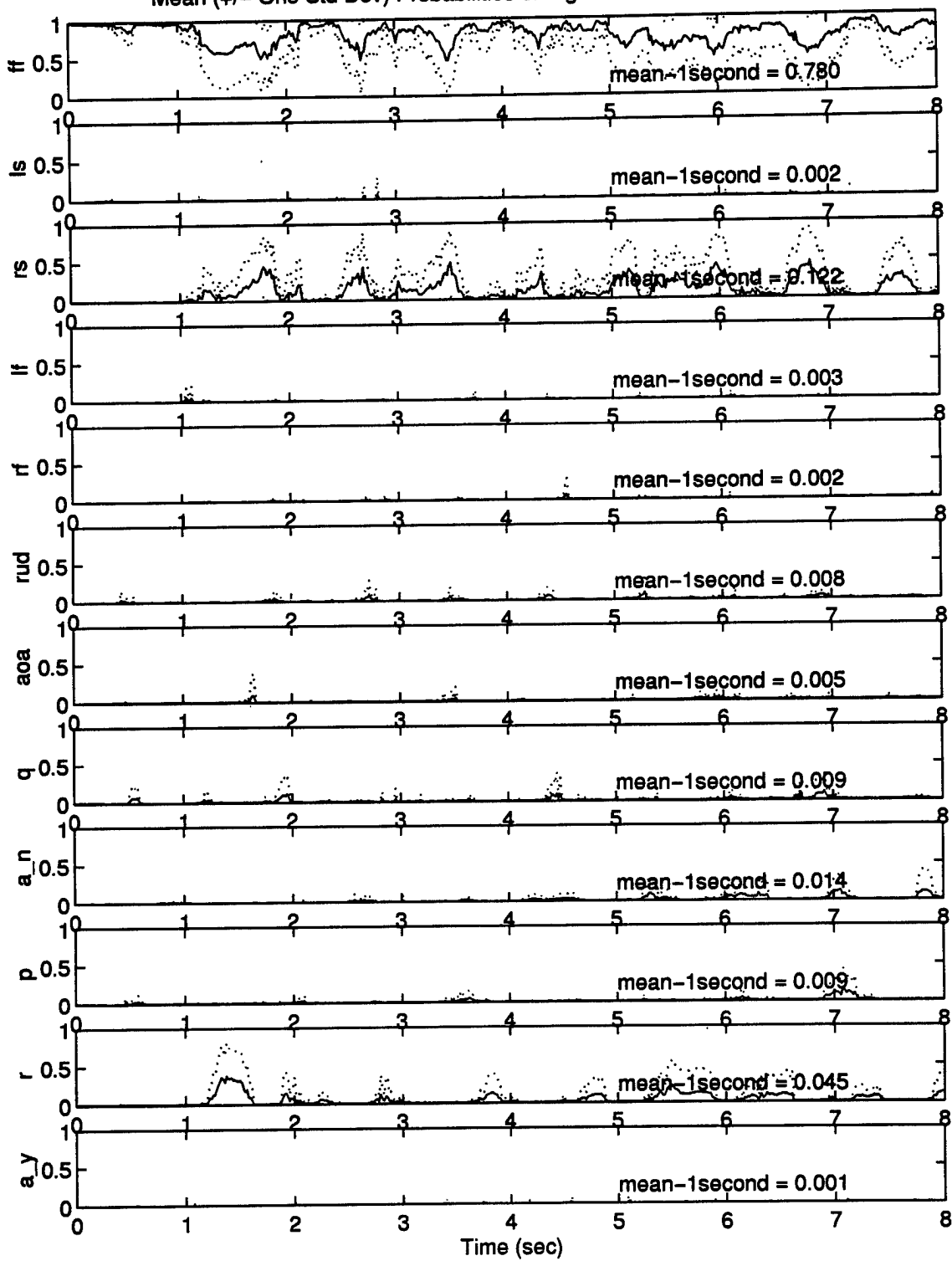
Mean (+/- One Std Dev) Probabilities of Fully Functional Aircraft: 10 runs



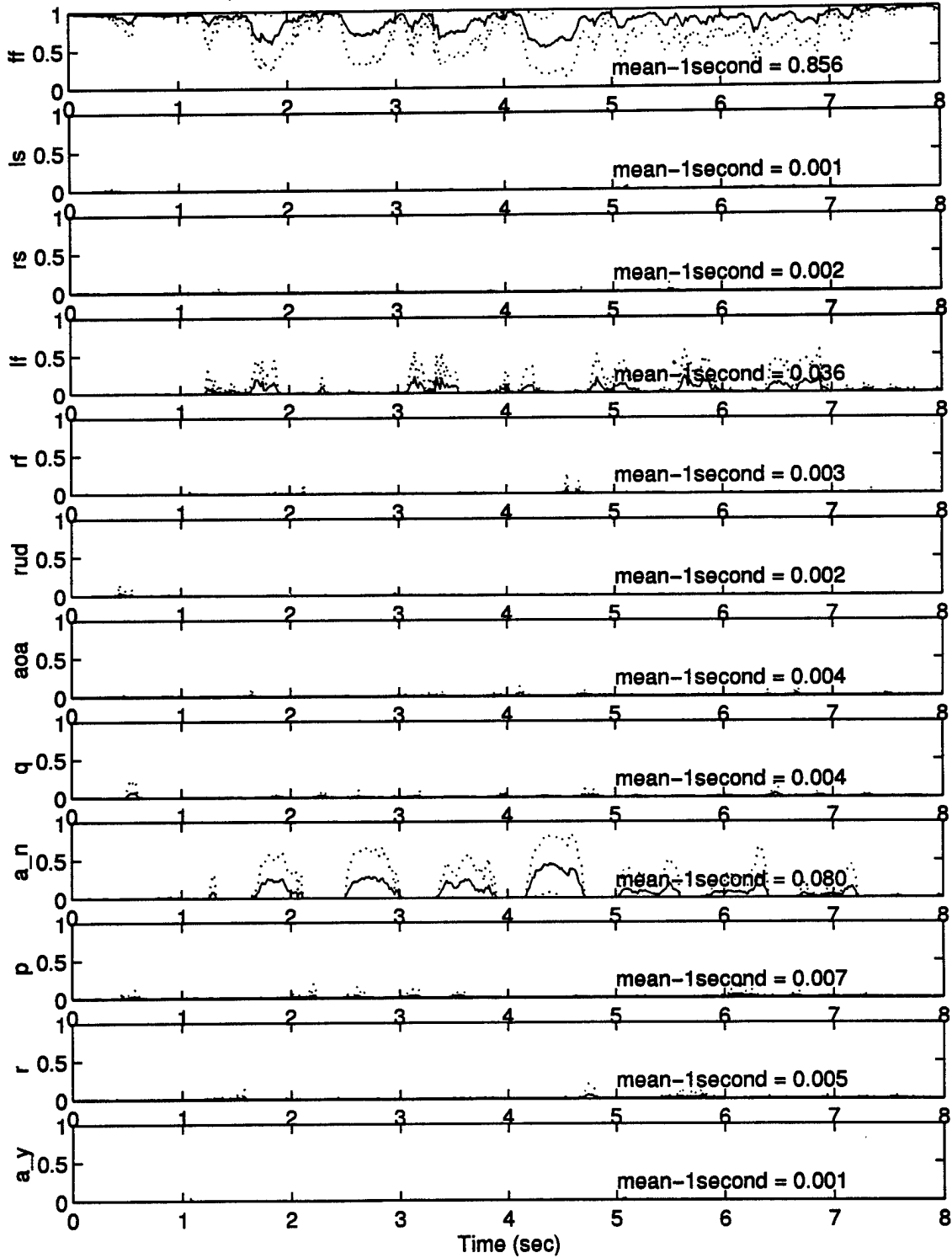
Mean (+/- One Std Dev) Probabilities of Left Stabilator Failure: 10 runs



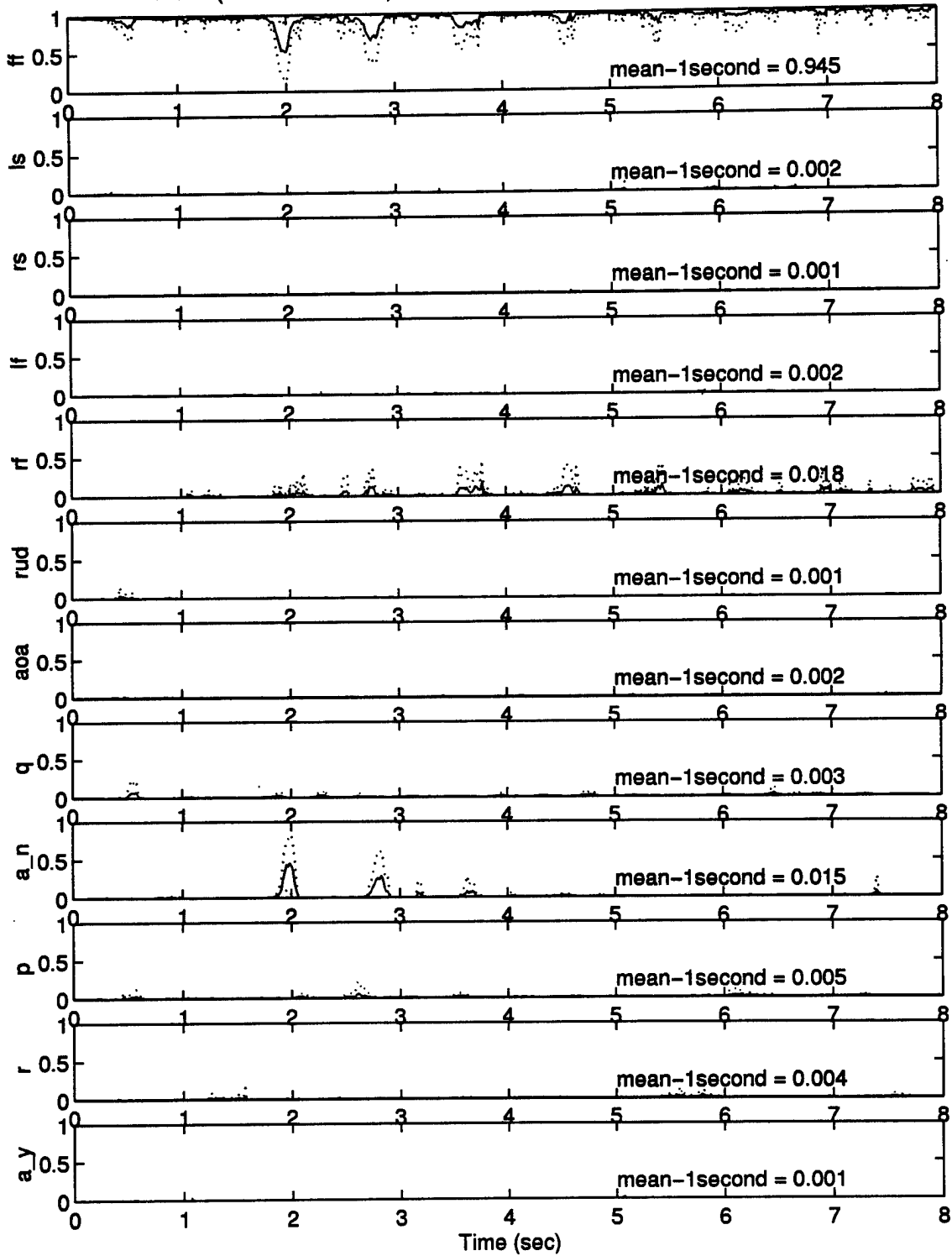
Mean (+/- One Std Dev) Probabilities of Right Stabilator Failure: 10 runs



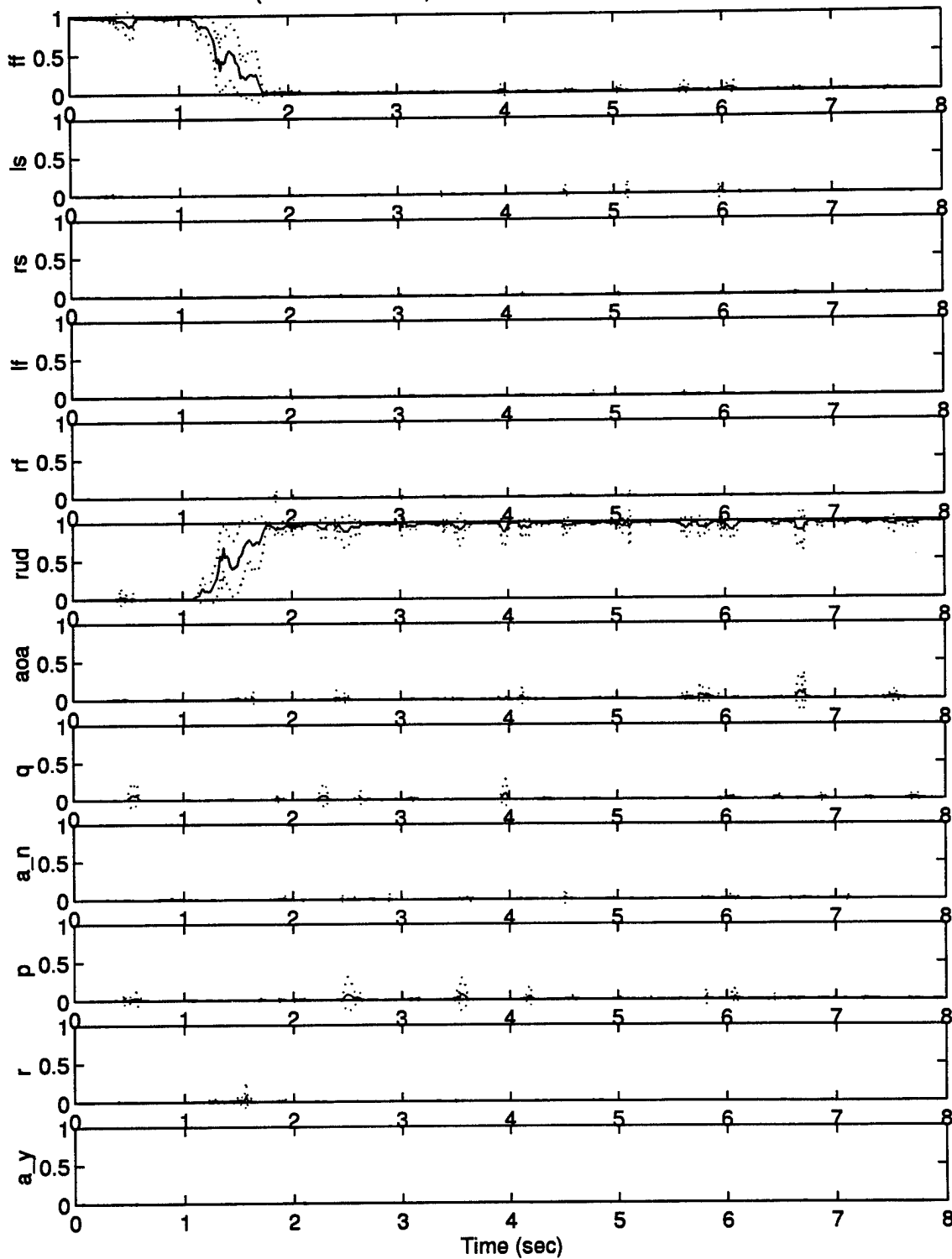
Mean (+/- One Std Dev) Probabilities of Left Flaperon Failure: 10 runs



Mean (+/- One Std Dev) Probabilities of Right Flaperon Failure: 10 runs



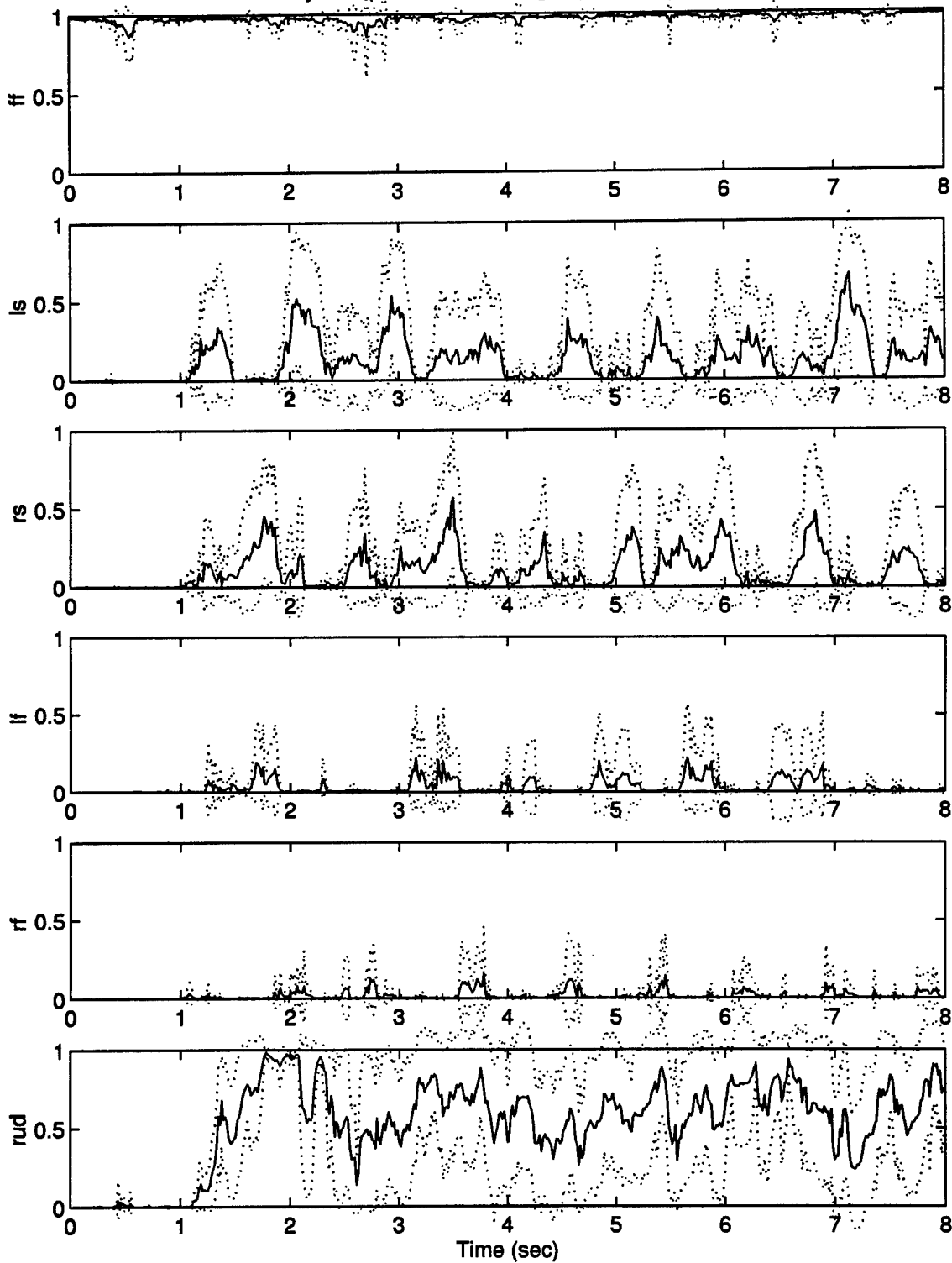
Mean (+/- One Std Dev) Probabilities of Rudder Failure: 10 runs



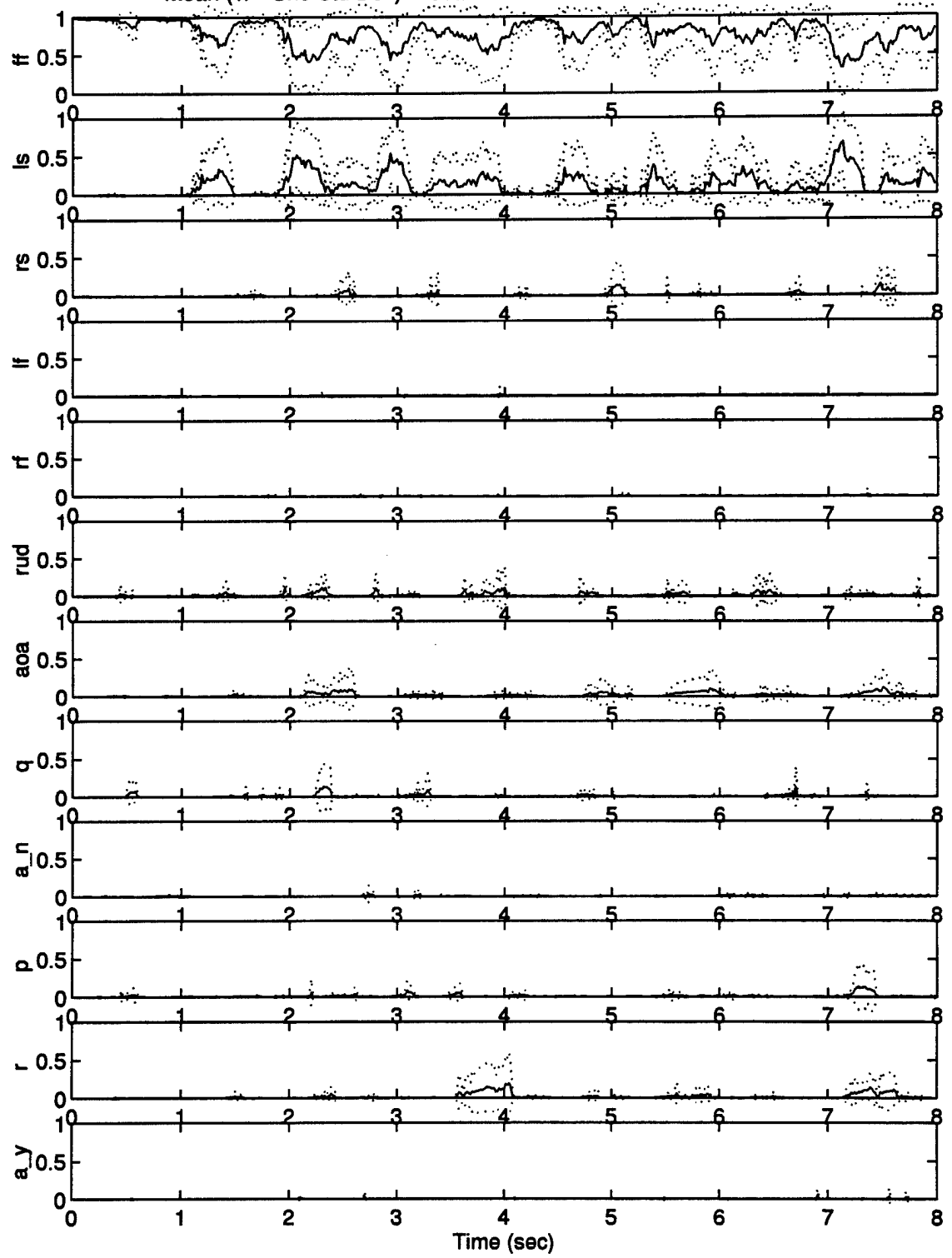
*Appendix C.2: Single 50% Actuator Impairments ($\epsilon = .5$), Control Redistribution 'ON', Dither
'ON', No Maneuvers*

This appendix contains the Probability Summary Plot and individual probability plots for cases of single, 50% ($\epsilon = .5$) actuator impairments, without aircraft maneuvering, but with Control Reconfiguration (Redistribution), and with control dithering (Section 4.13.2).

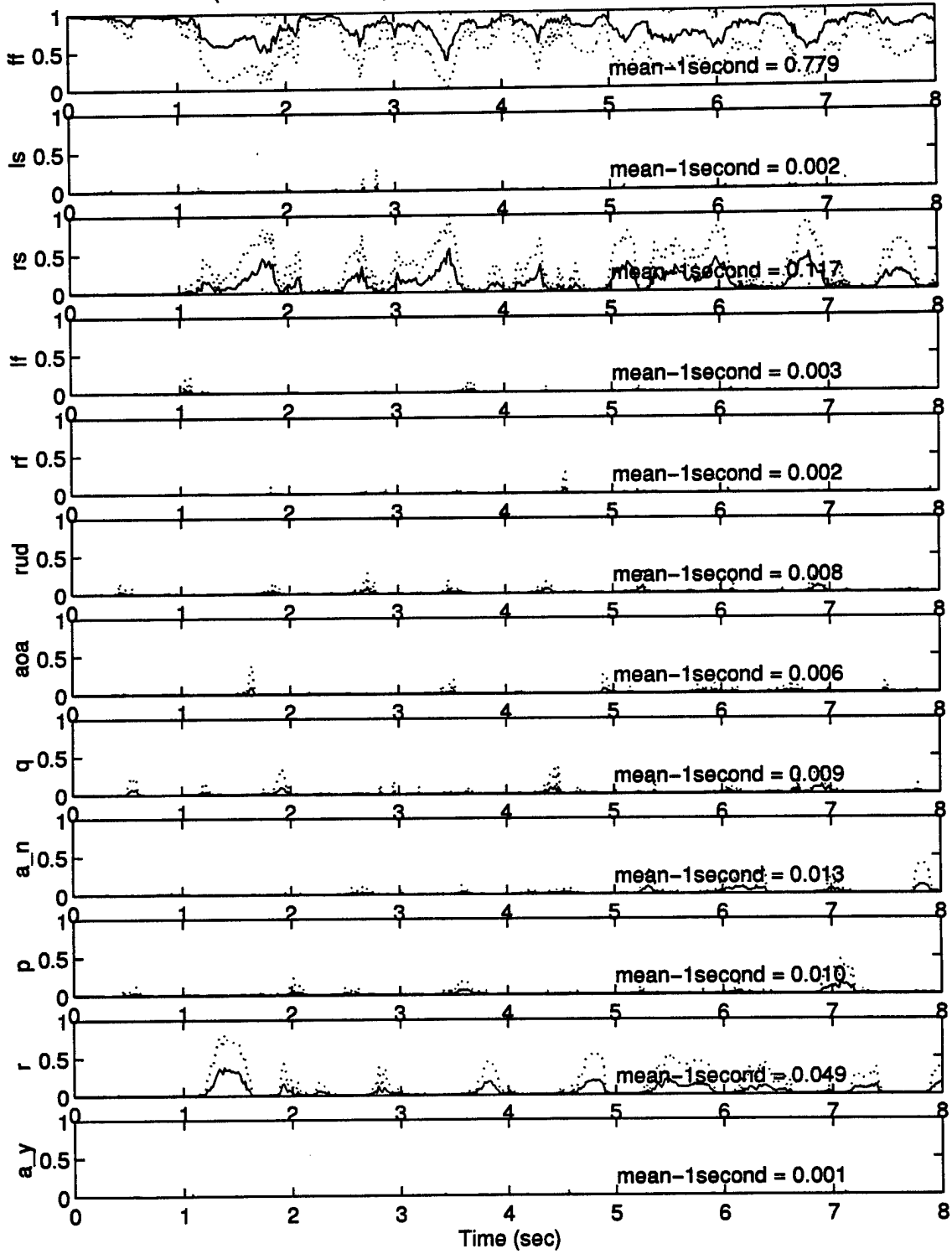
Summary Plot (with Mean \pm Sigma) for recon50: 10 runs



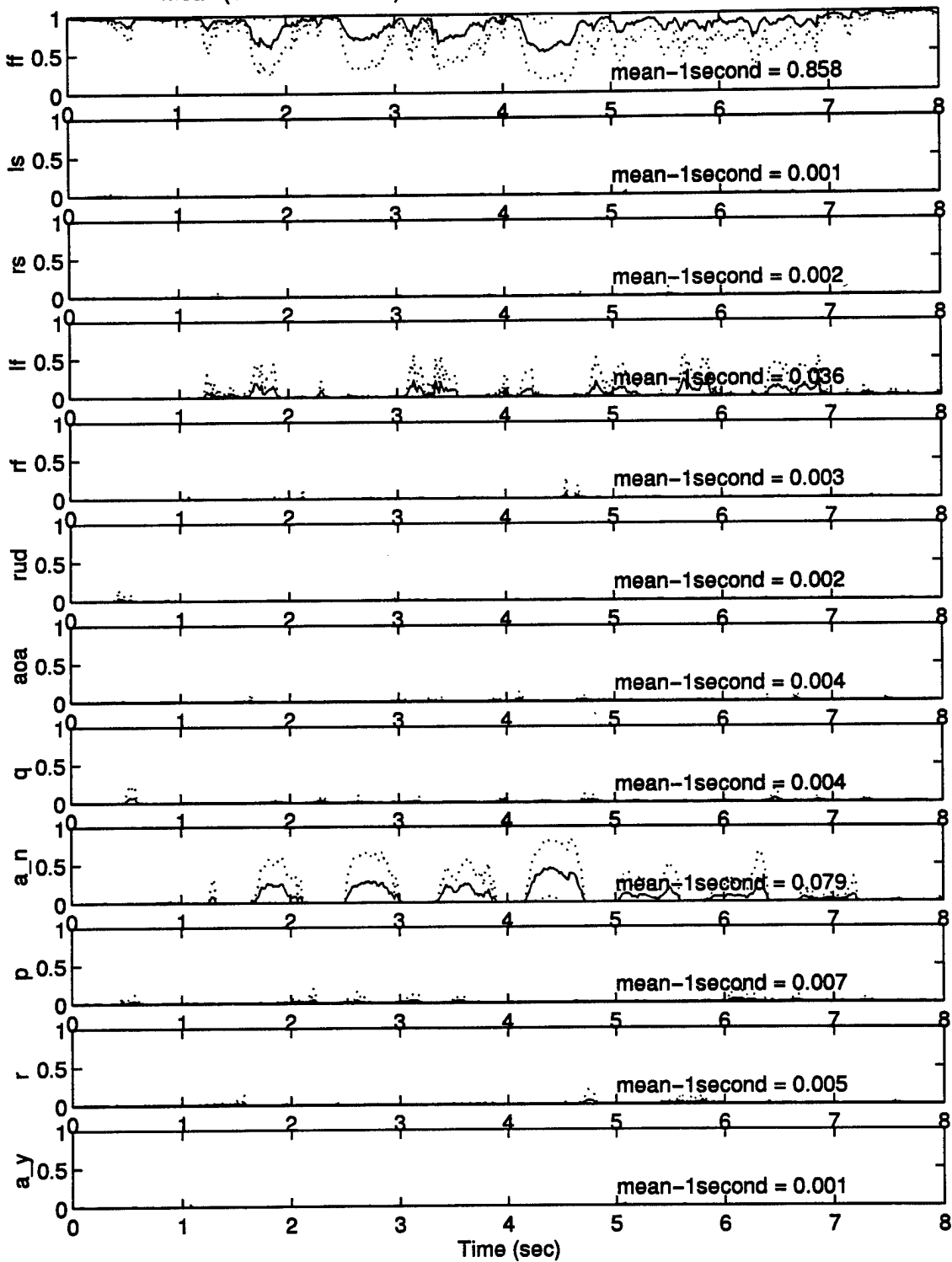
Mean (+/- One Std Dev) Probabilities of Left Stabilator Failure: 10 runs



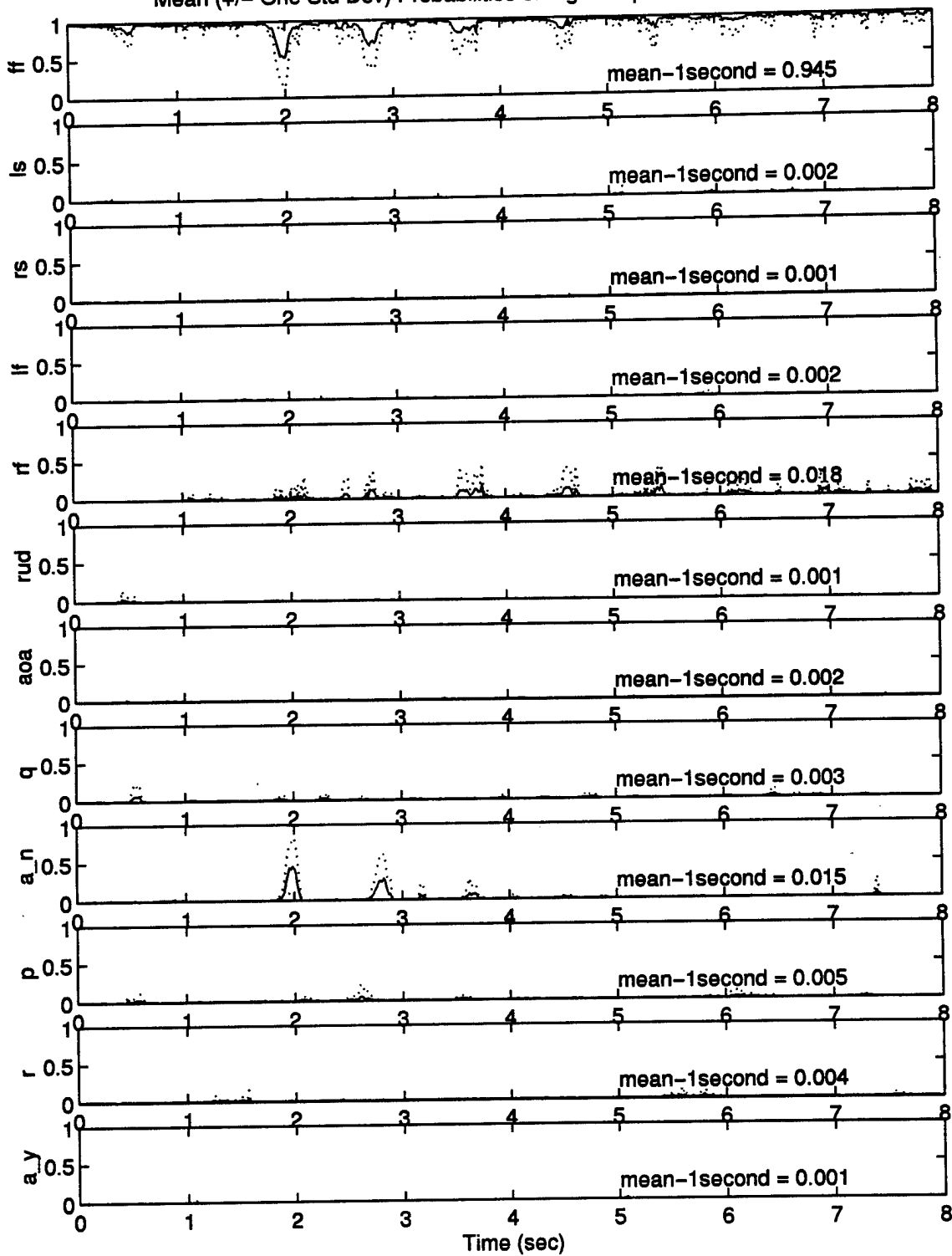
Mean (+/- One Std Dev) Probabilities of Right Stabilator Failure: 10 runs



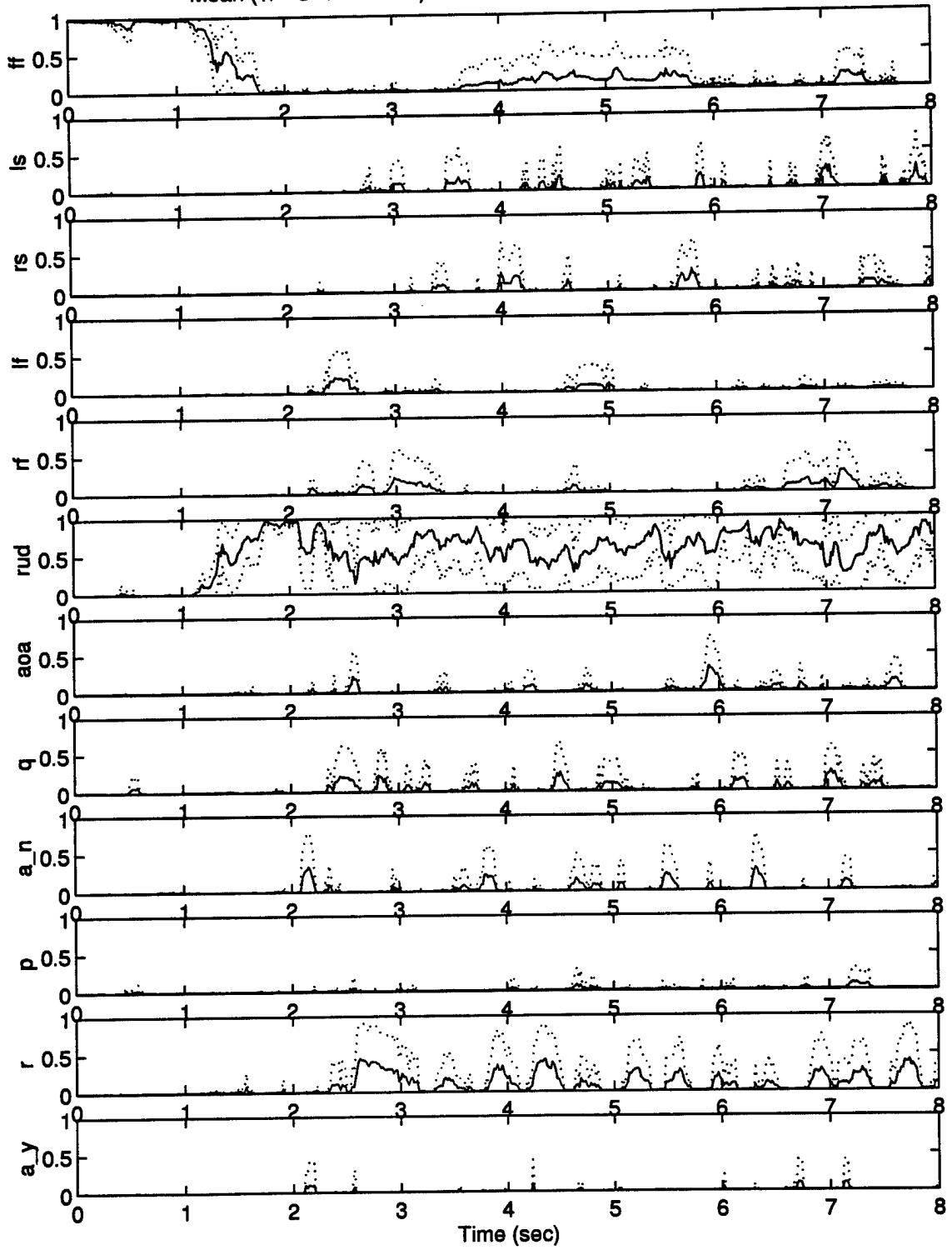
Mean (+/- One Std Dev) Probabilities of Left Flaperon Failure: 10 runs



Mean (+/- One Std Dev) Probabilities of Right Flaperon Failure: 10 runs



Mean (+/- One Std Dev) Probabilities of Rudder Failure: 10 runs



*Appendix D.1: Dual, Total Actuator ($\epsilon = 0$) and Total-Actuator / Total -Sensor Impairments,
Control Redistribution 'ON', Dither 'ON', No Maneuvers*

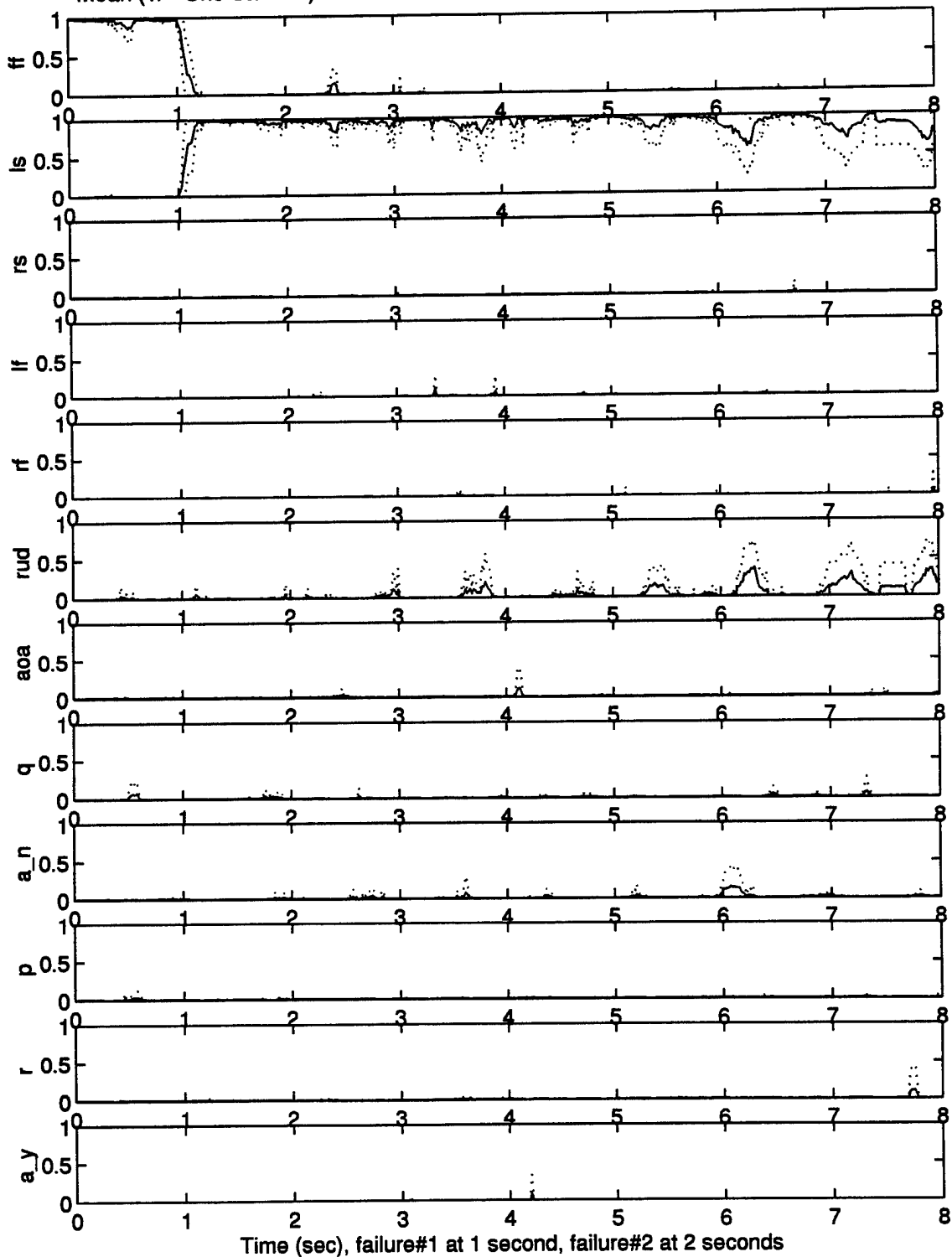
This appendix contains the individual probability plots for “total actuator / total actuator” and “total actuator / total sensor” dual impairment scenarios, *with* Control Reconfiguration (Redistribution) and with control dithering (Section 4.11.3). The first impairment is inserted at 1 second, followed by the second impairment at 2 seconds, and in all cases, there is no aircraft maneuvering. Table D.1 on the following page lists the impairment cases, by case number, which are to be found in this appendix. The leftmost column of Table D.1 represents the first impairment occurring at 1 second, while the top row represents the second impairment occurring at 2 seconds. The table entries list the failure codes found in the plot titles for the failure case represented by the table row and column. **Bold** entries correspond to cases of no second impairment. As an example, the entry for a left stabilator (LS) impairment at 1 second, followed by a right flaperon (RF) impairment at 2 seconds is found in entry ‘(LS, RF)’ in the table, and the corresponding failure case is ‘fail01.04’. The probability plot will contain this code (‘fail01.04’) in the plot title. In fact, for this specific case, the plot title is: “Mean (+ / - One Std Dev) Dual-fail Probabilities of fail01.04 with reconfiguration: 10 runs”. The reader should not be confused by the fact that, for cases of total sensor second impairments, there is an extra set of zeros (example: ‘fail001.006’ vs. ‘fail01.06’, as one may anticipate) in the failure code. The dual, *total* actuator impairment cases were run at an earlier date, before the additional zero placeholders were added to the plotting routine to provide for meaningful plot titles during *partial* impairment scenarios to come. The reader is also reminded that, after the switch to the Level ‘1’ filter bank, the meanings of the probability traces in the plots (except for the fully functional trace, which retains the same meaning) change to that of the first impairment *plus* the second impairment.

Second Impairment

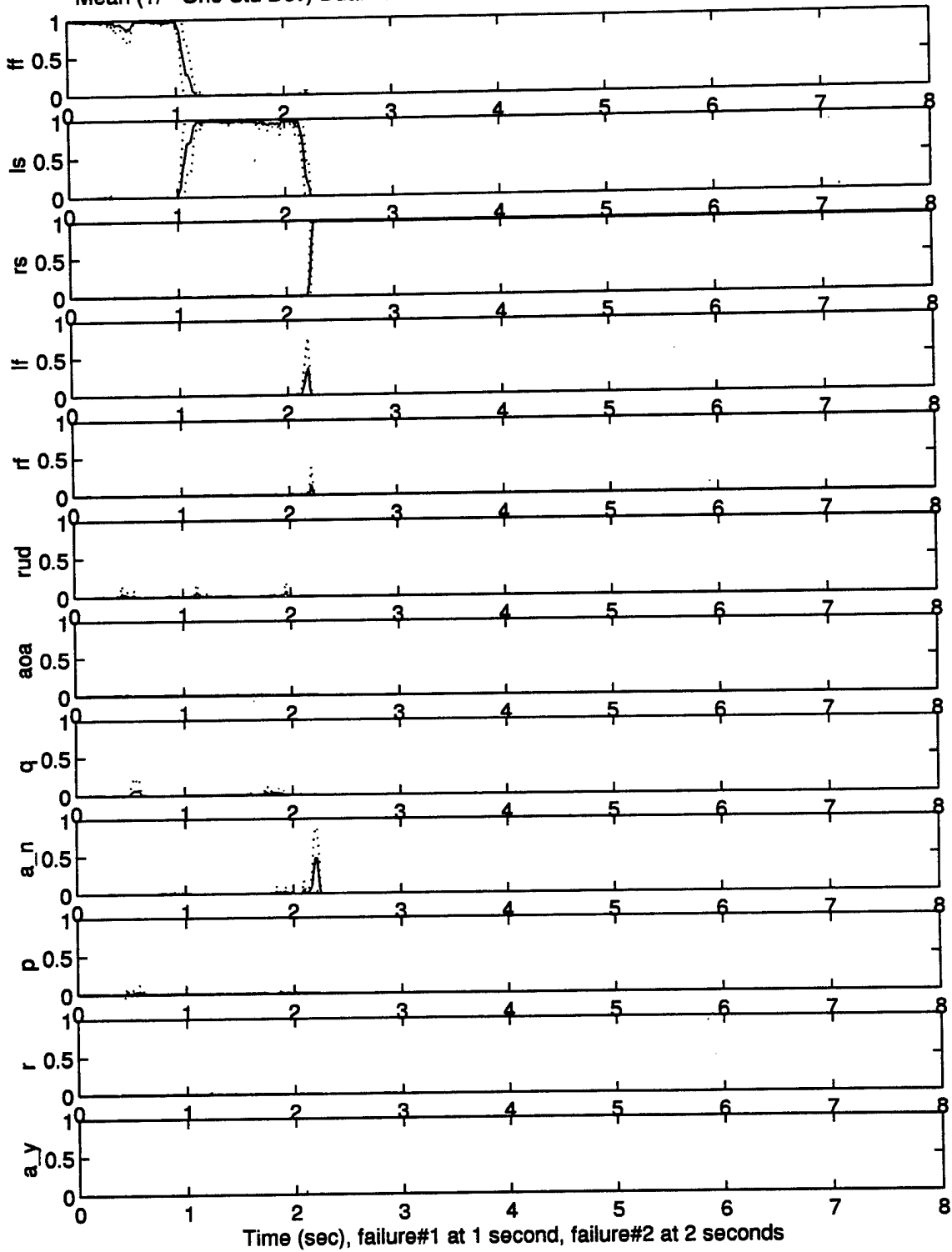
	LS (100%)	RS (100%)	LF (100%)	RF (100%)	RUD (100%)	AOA (100%)	Q (100%)	A_n (100%)	P (100%)	R (100%)	A_y (100%)
LS (100%)	fail01.00	fail01.02	fail01.03	fail01.04	fail01.05	fail001.006	fail001.007	fail001.008	fail001.009	fail001.0010	fail001.0011
RS (100%)	fail02.01	fail02.00	fail02.03	fail02.04	fail02.05	fail002.006	fail002.007	fail002.008	fail002.009	fail002.0010	fail002.0011
LF (100%)	fail03.01	fail03.02	fail03.00	fail03.04	fail03.05	fail003.006	fail003.007	fail003.008	fail003.009	fail003.0010	fail003.0011
RF (100%)	fail04.01	fail04.02	fail04.03	fail04.00	fail04.05	fail004.006	fail004.007	fail004.008	fail004.009	fail004.0010	fail004.0011
RUD (100%)	fail05.01	fail05.02	fail05.03	fail05.04	fail05.00	fail005.006	fail005.007	fail005.008	fail005.009	fail005.0010	fail005.0011

Table D.1 A Listing of All Probability Plots Found in Appendix D.1 by Failure Case

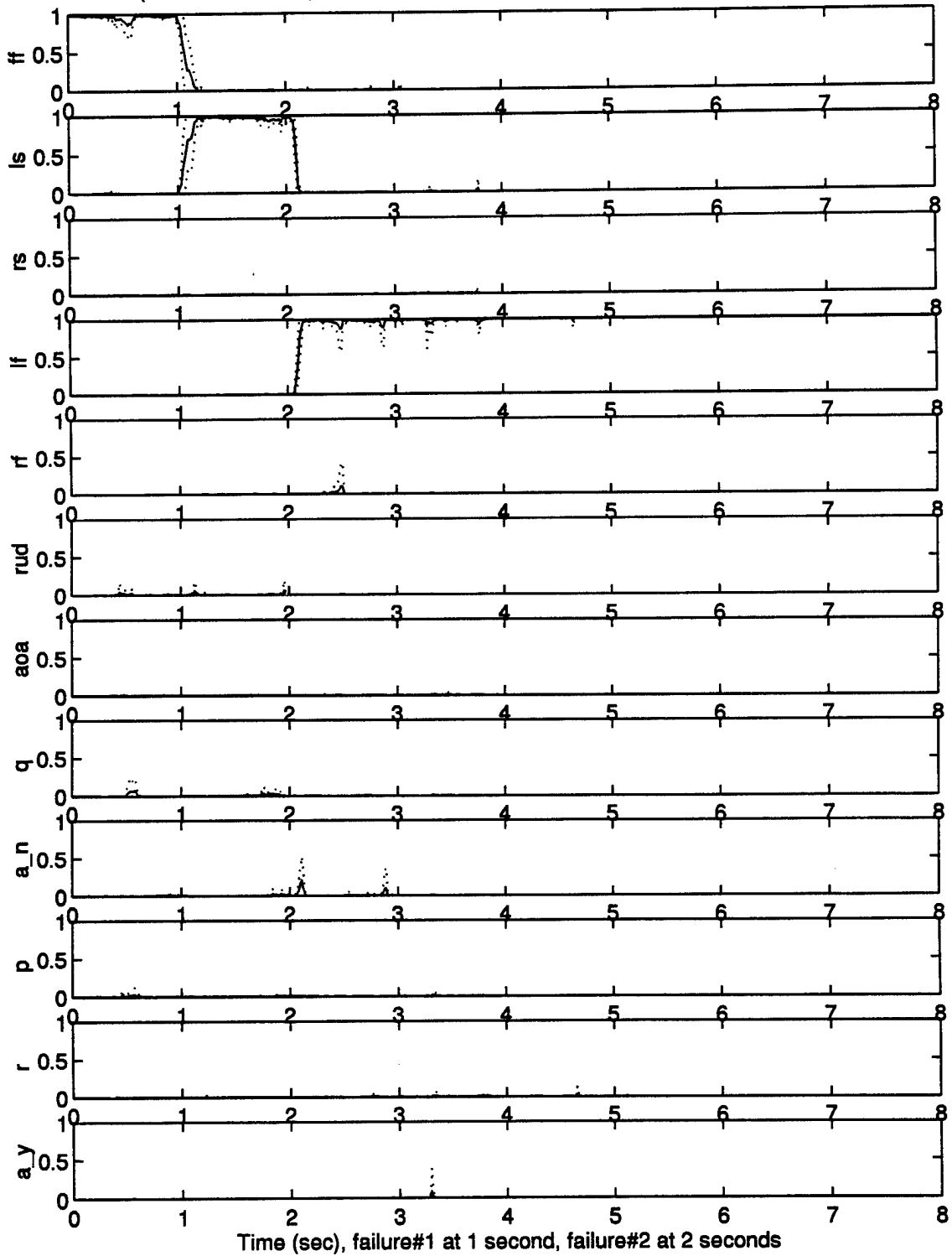
Mean (+/- One Std Dev) Dual-fail Probabilities of fail01.00 with reconfiguration: 10 runs



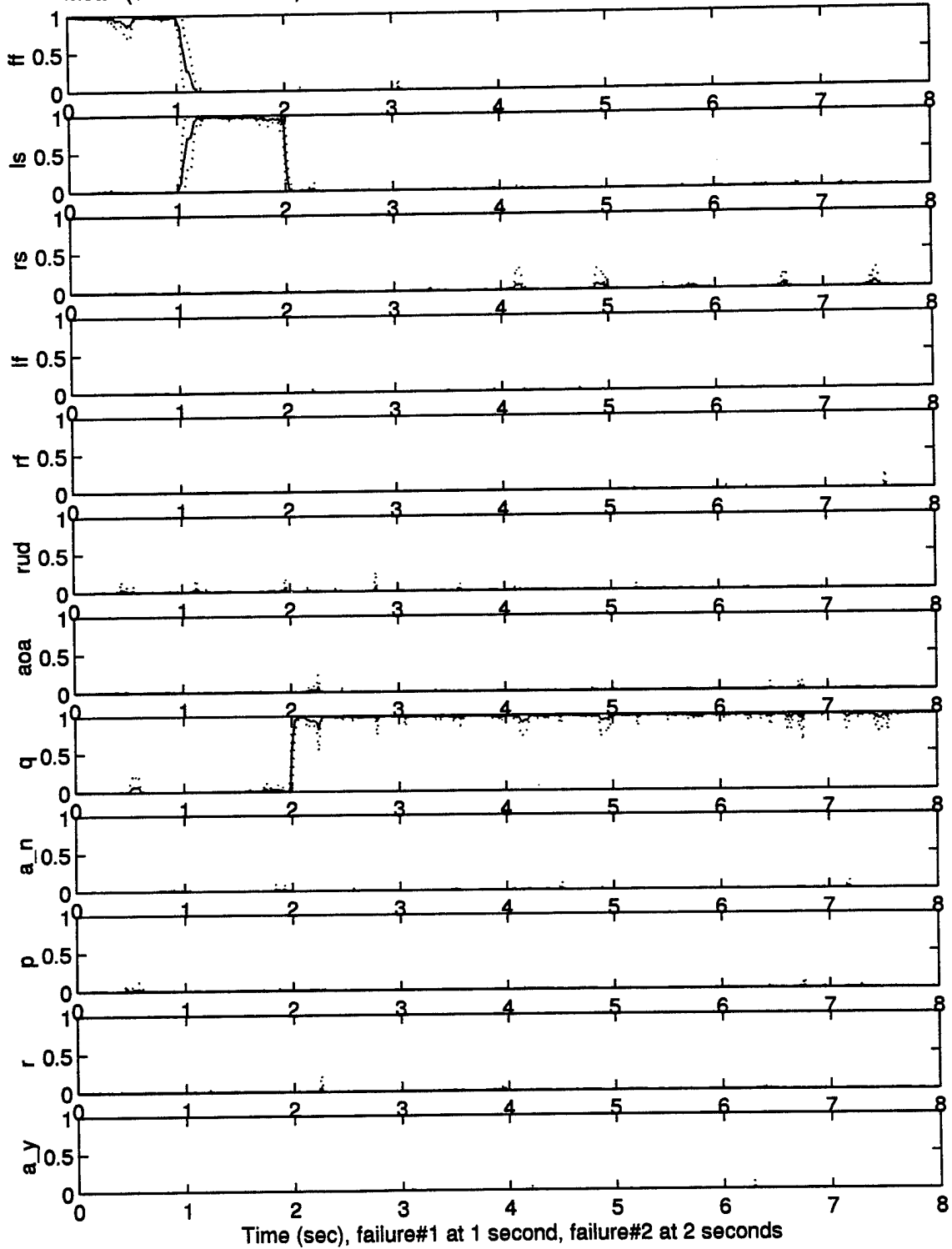
Mean (+/- One Std Dev) Dual-fail Probabilities of fail01.02 with reconfiguration: 10 runs



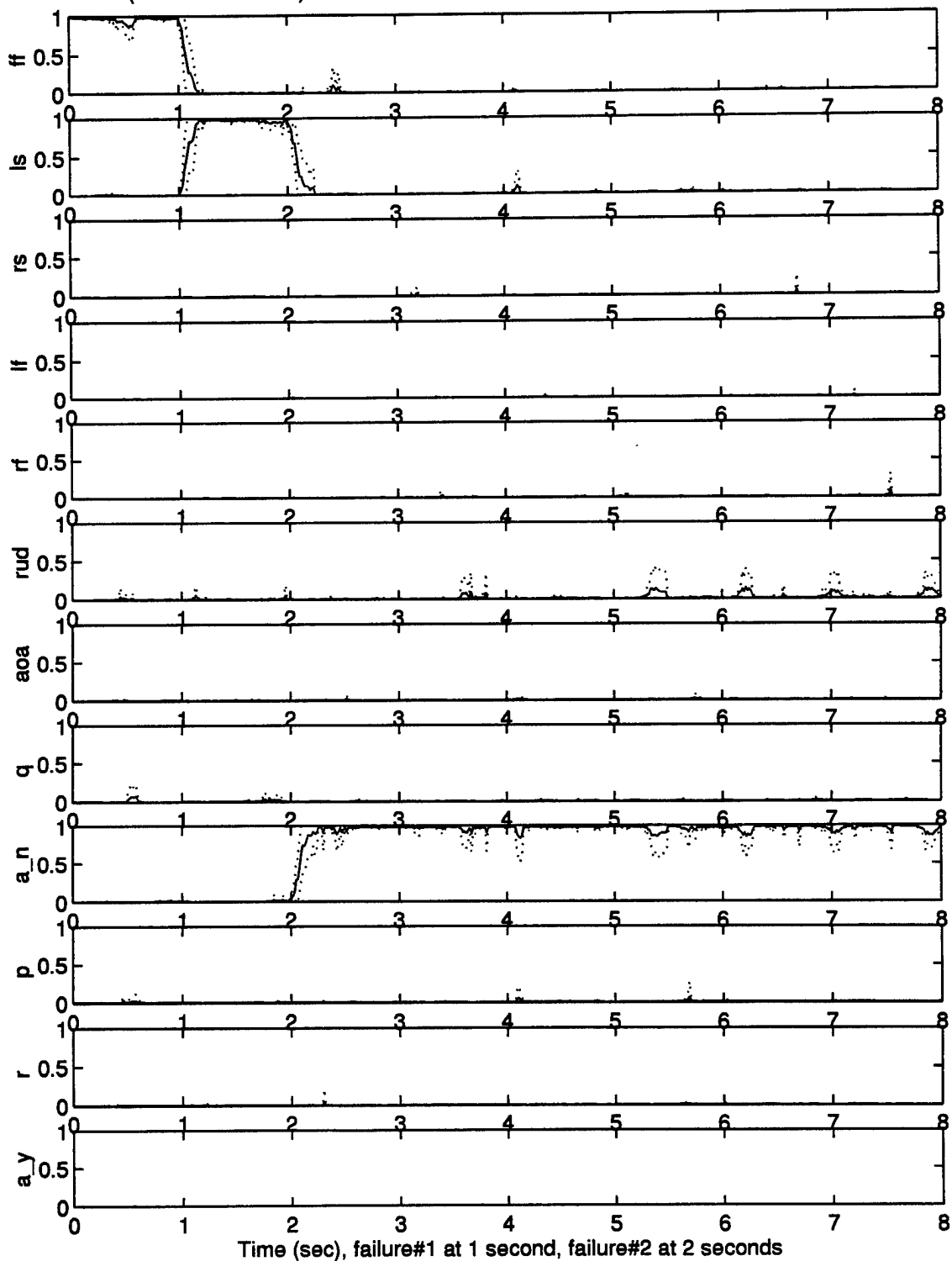
Mean (+/- One Std Dev) Dual-fail Probabilities of fail01.03 with reconfiguration: 10 runs



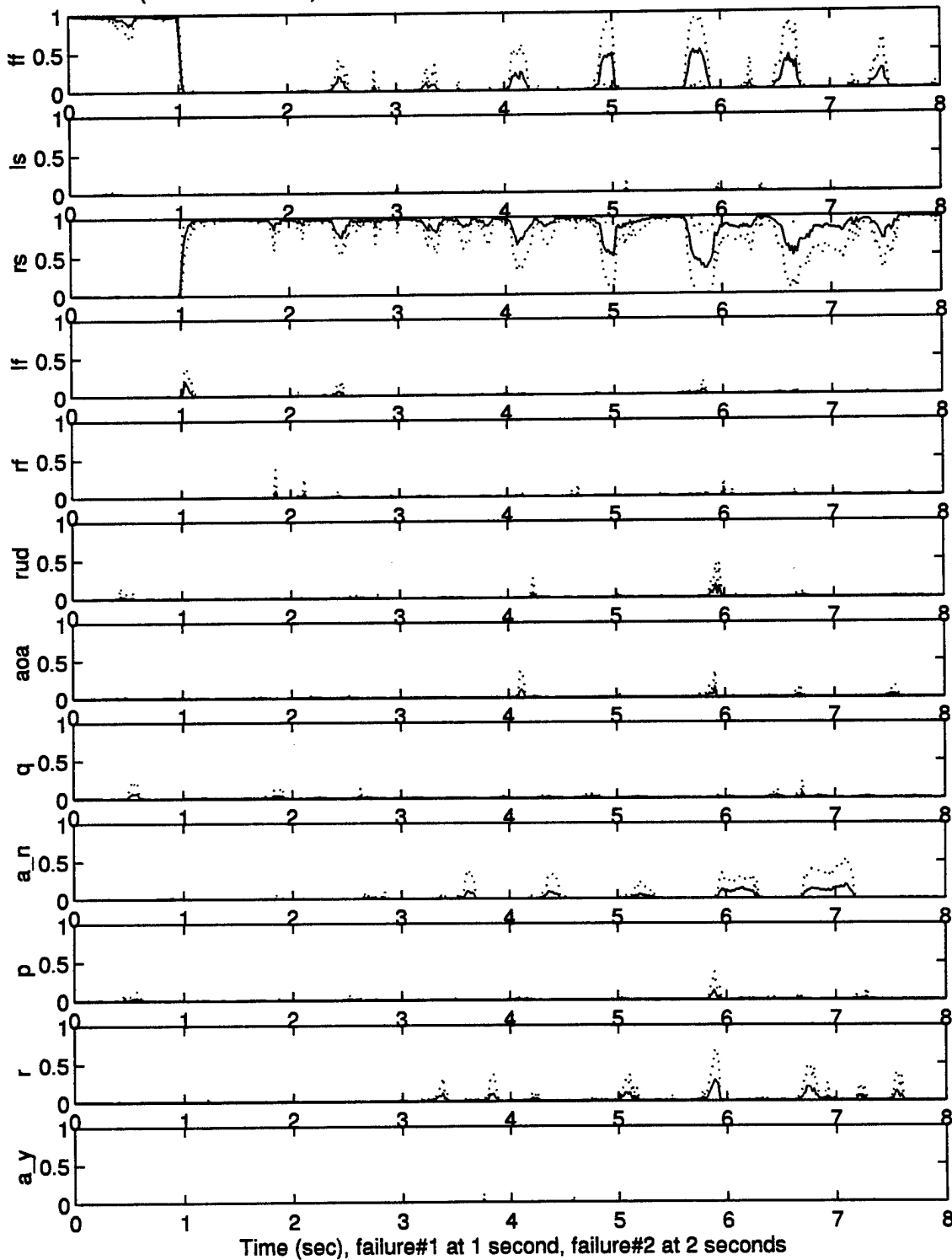
Mean (+/- One Std Dev) Dual-fail Probabilities of fail001.007 with reconfiguration: 10 runs



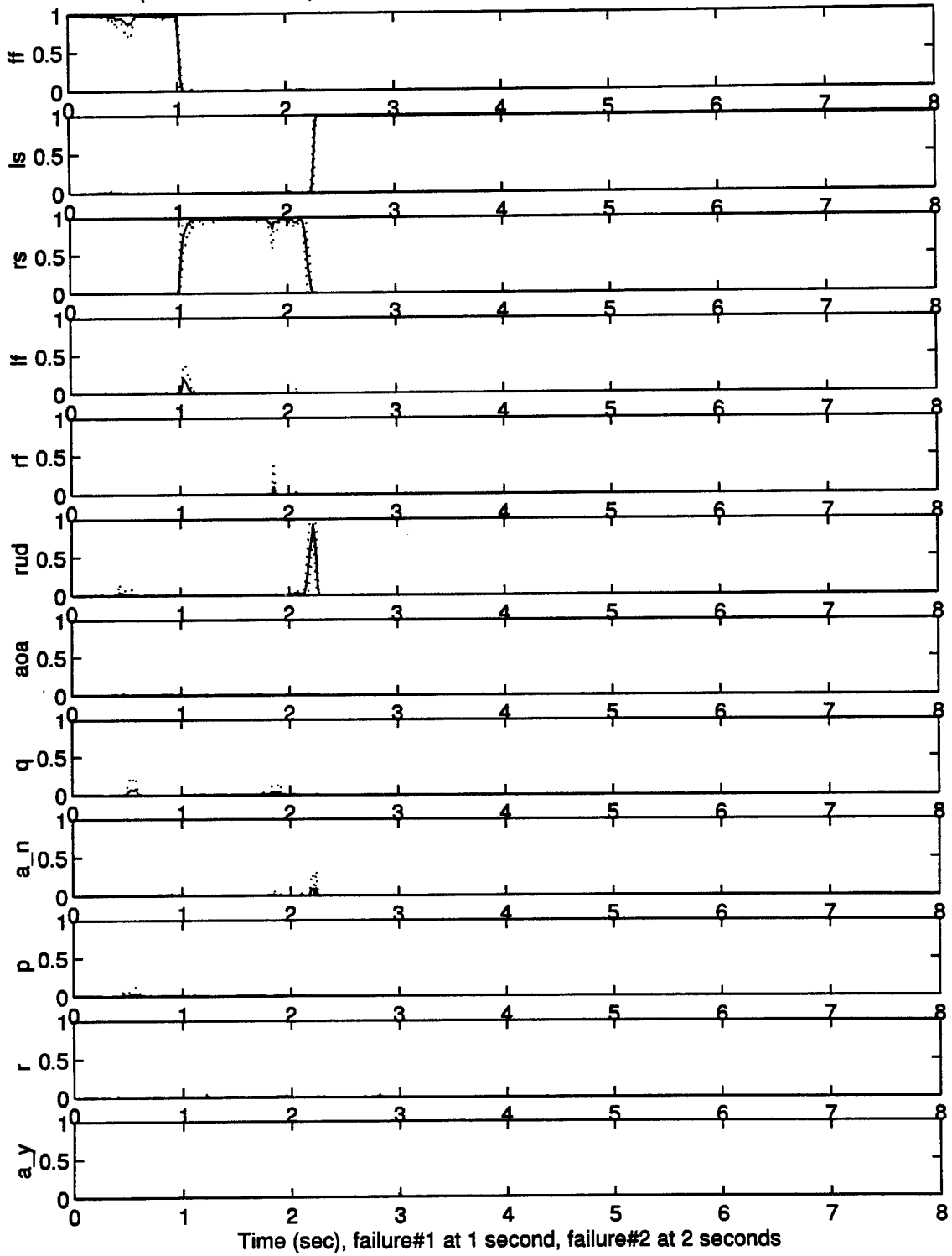
Mean (+/- One Std Dev) Dual-fail Probabilities of fail001.008 with reconfiguration: 10 runs



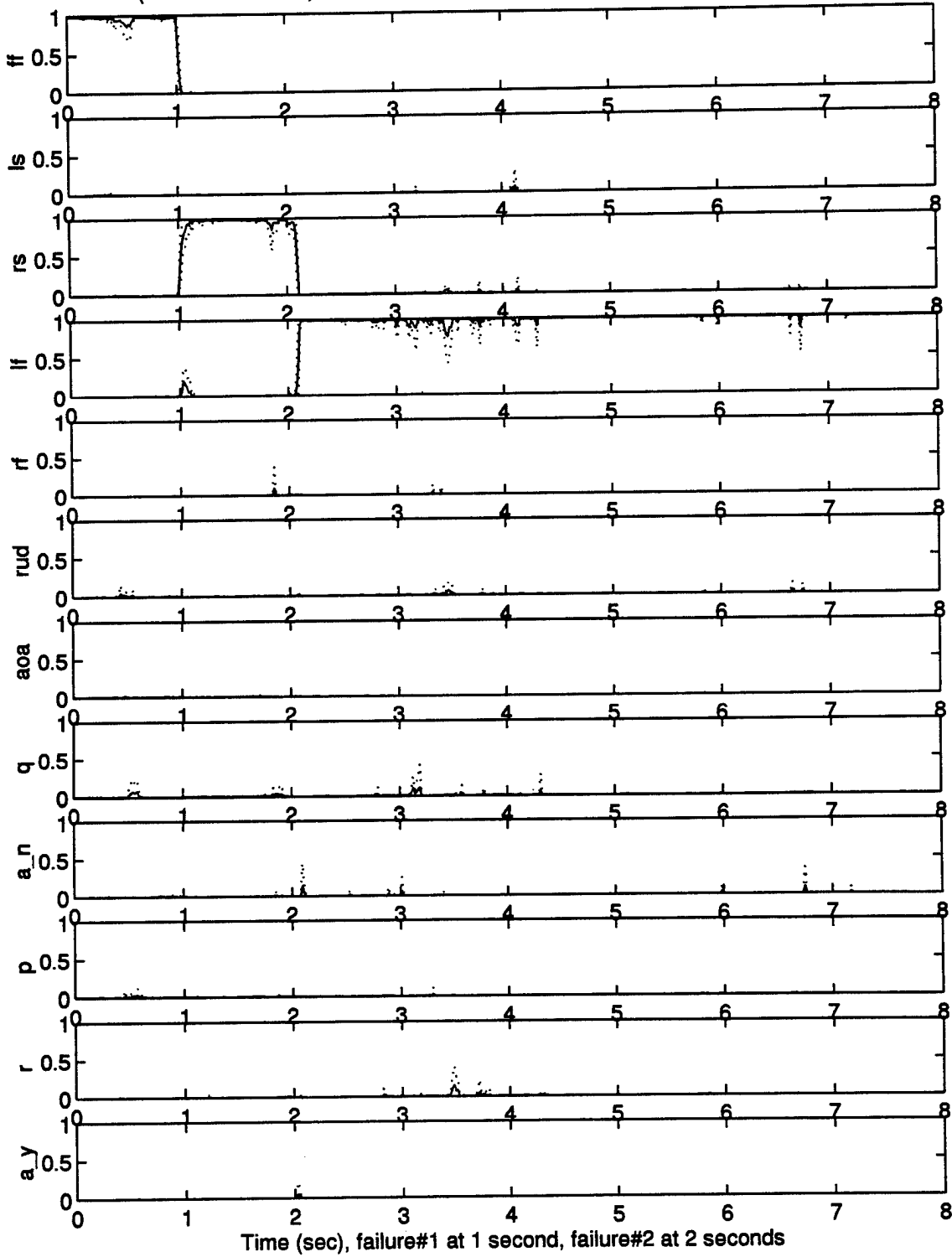
Mean (+/- One Std Dev) Dual-fail Probabilities of fail02.00 with reconfiguration: 10 runs



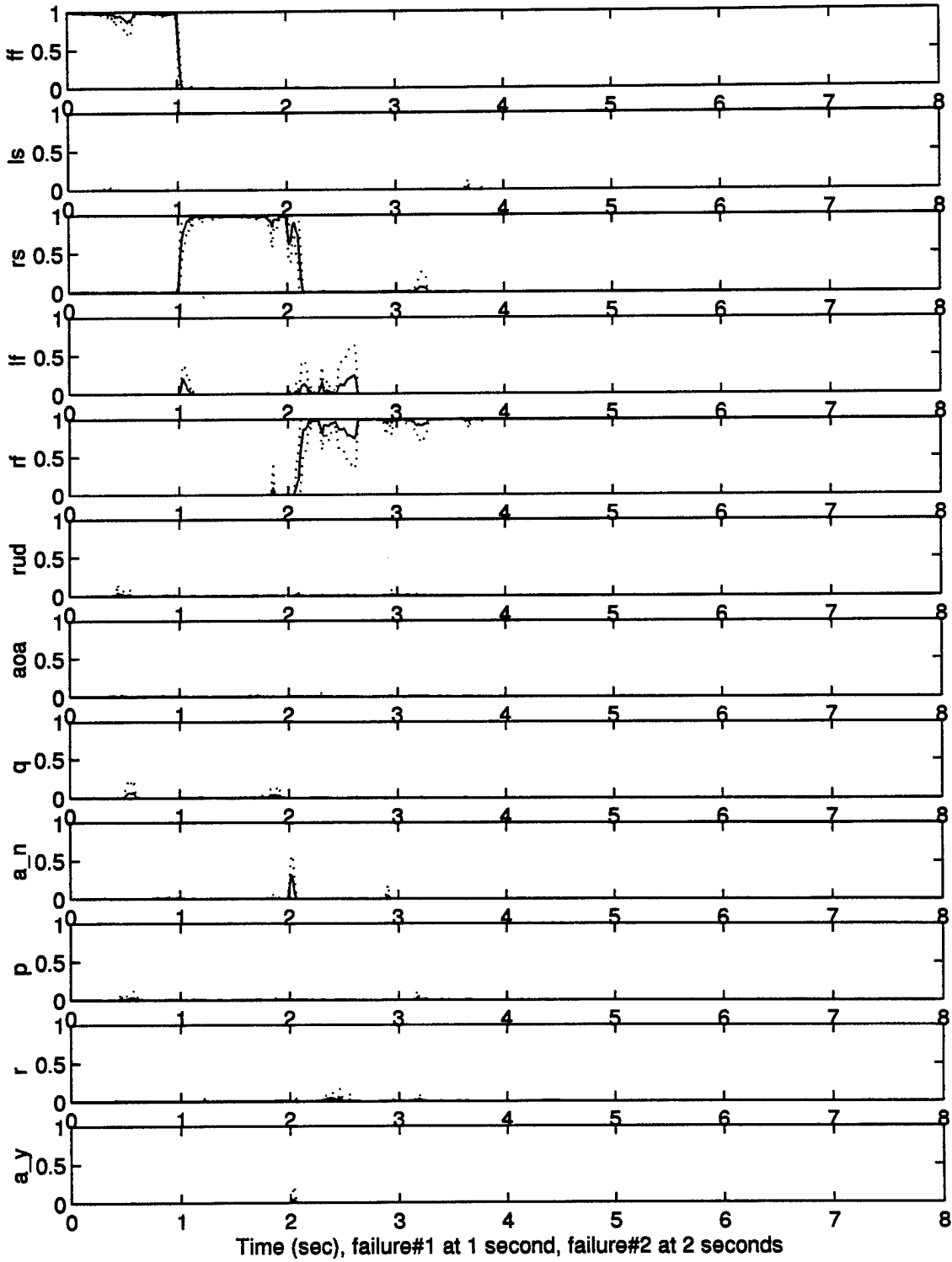
Mean (+/- One Std Dev) Dual-fail Probabilities of fail02.01 with reconfiguration: 10 runs



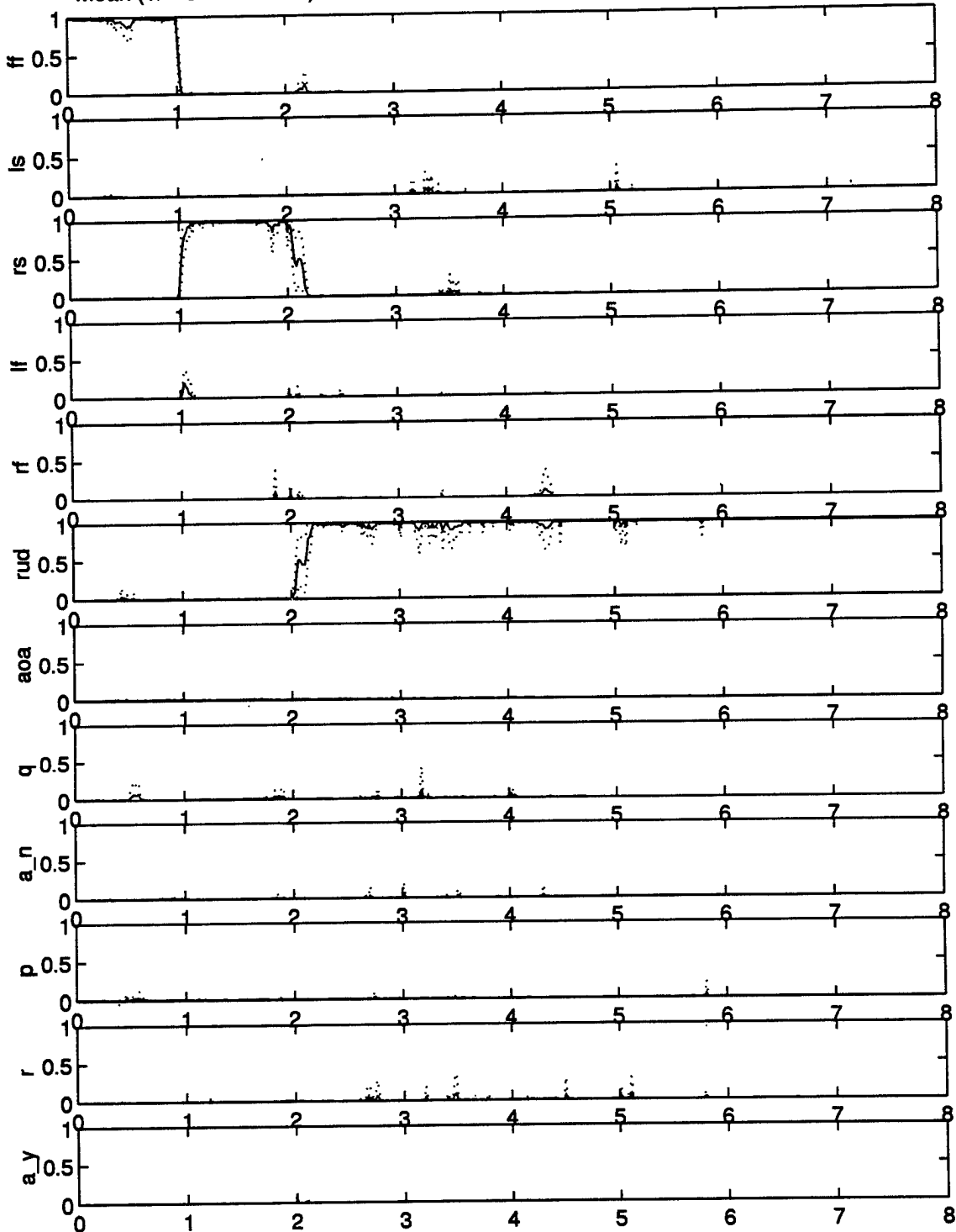
Mean (+/- One Std Dev) Dual-fail Probabilities of fail02.03 with reconfiguration: 10 runs



Mean (+/- One Std Dev) Dual-fail Probabilities of fail02.04 with reconfiguration: 10 runs

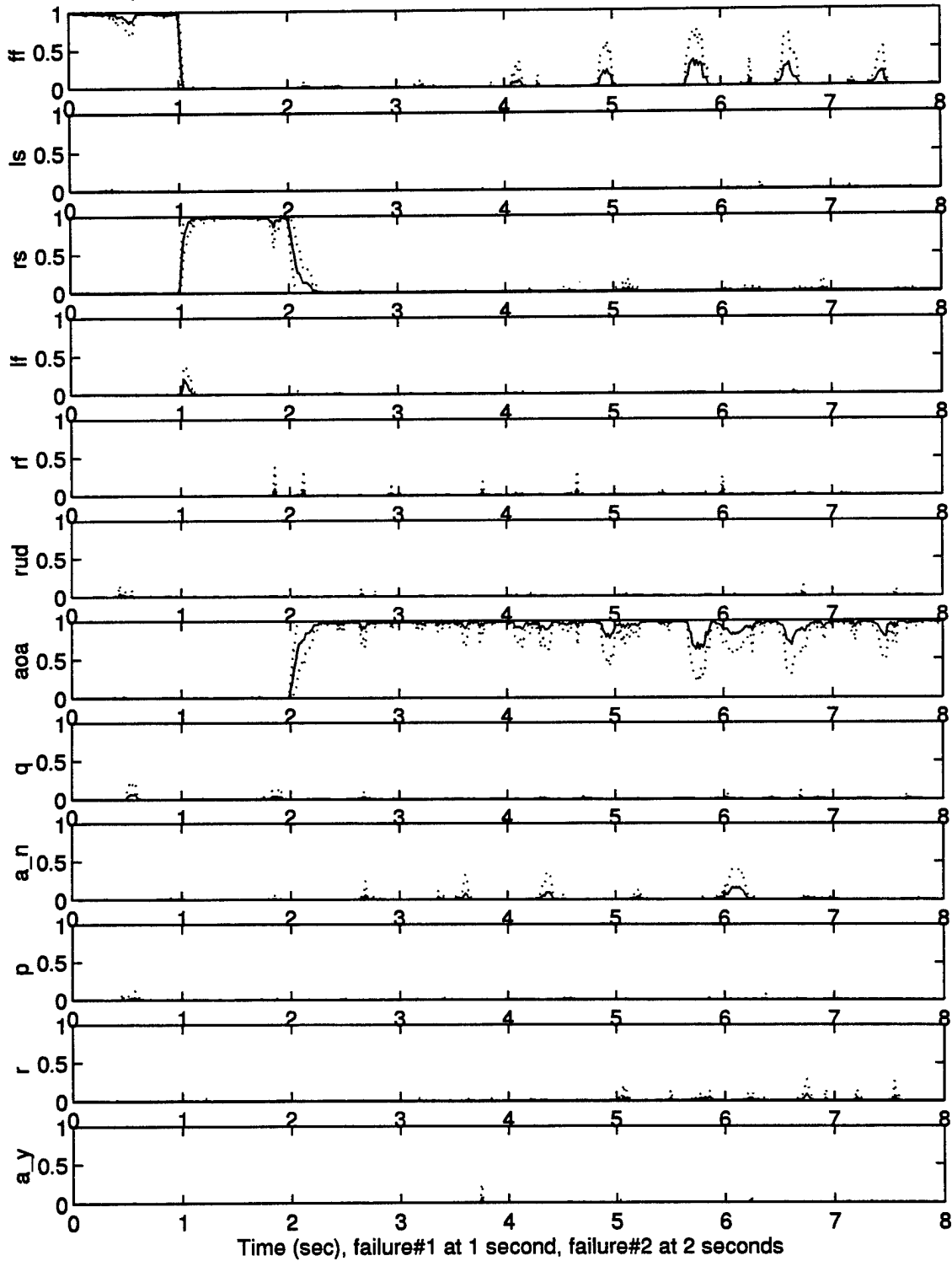


Mean (+/- One Std Dev) Dual-fail Probabilities of fail02.05 with reconfiguration: 10 runs

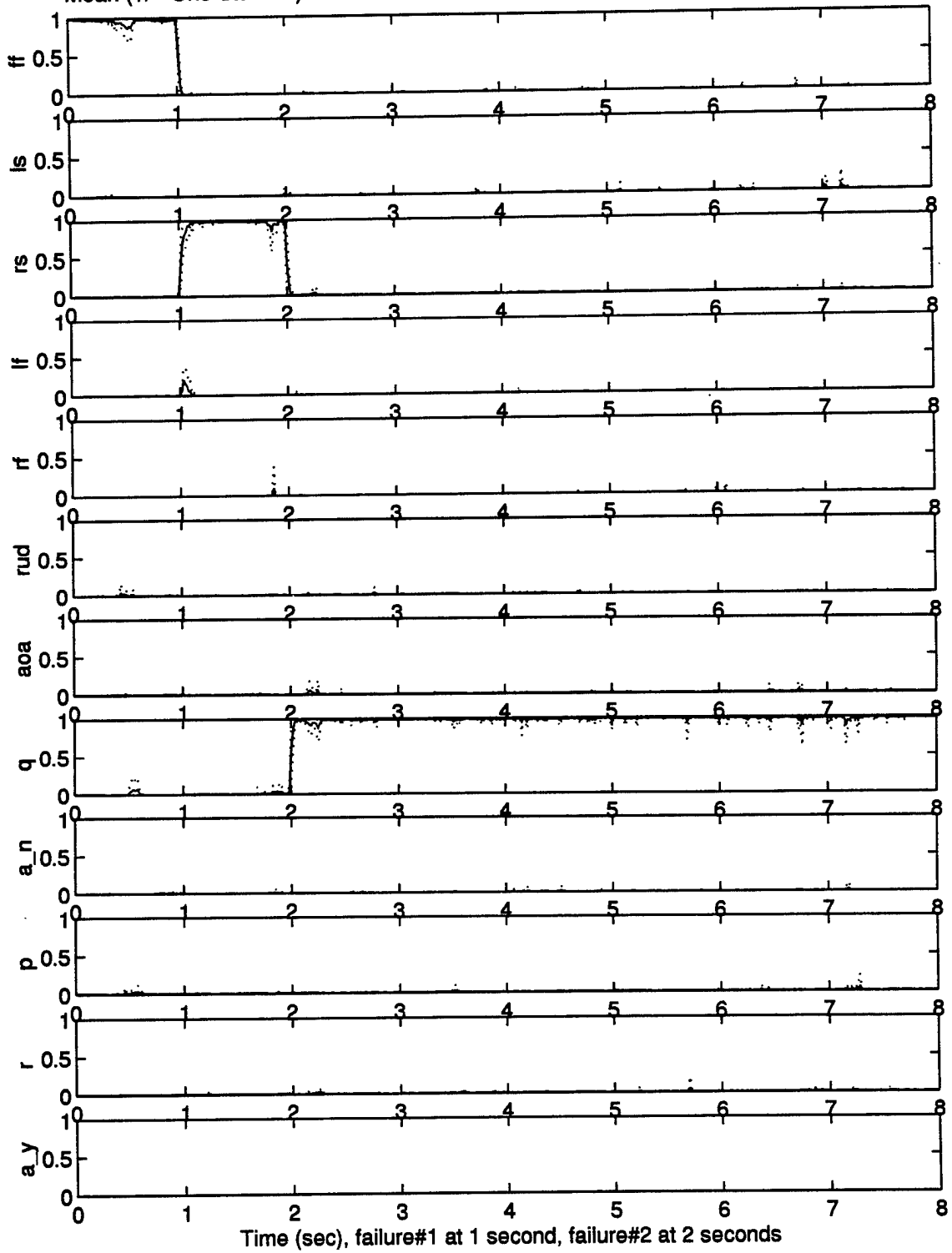


Time (sec), failure#1 at 1 second, failure#2 at 2 seconds

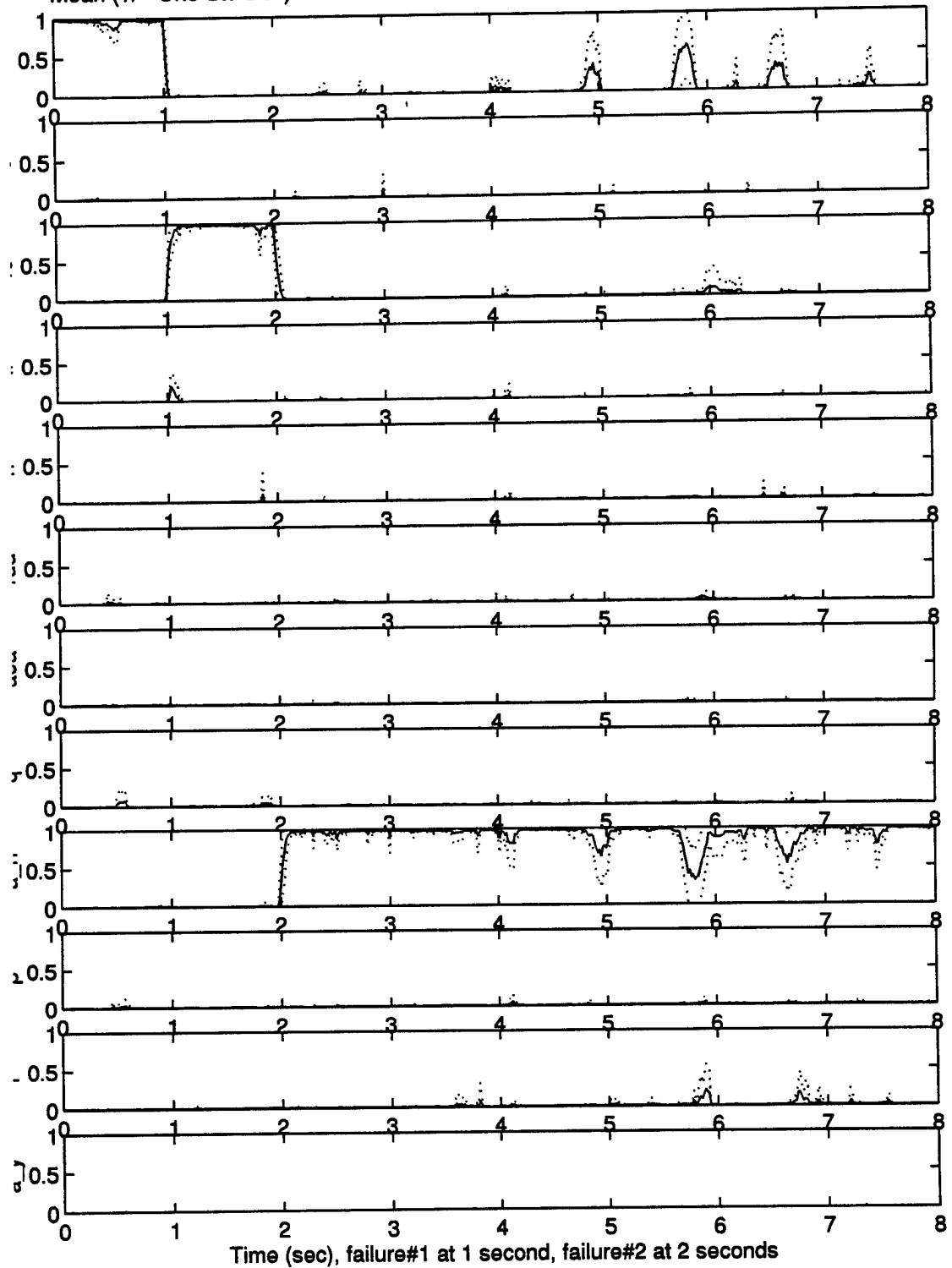
Mean (+/- One Std Dev) Dual-fail Probabilities of fail002.006 with reconfiguration: 10 runs



Mean (+/- One Std Dev) Dual-fail Probabilities of fail002.007 with reconfiguration: 10 runs

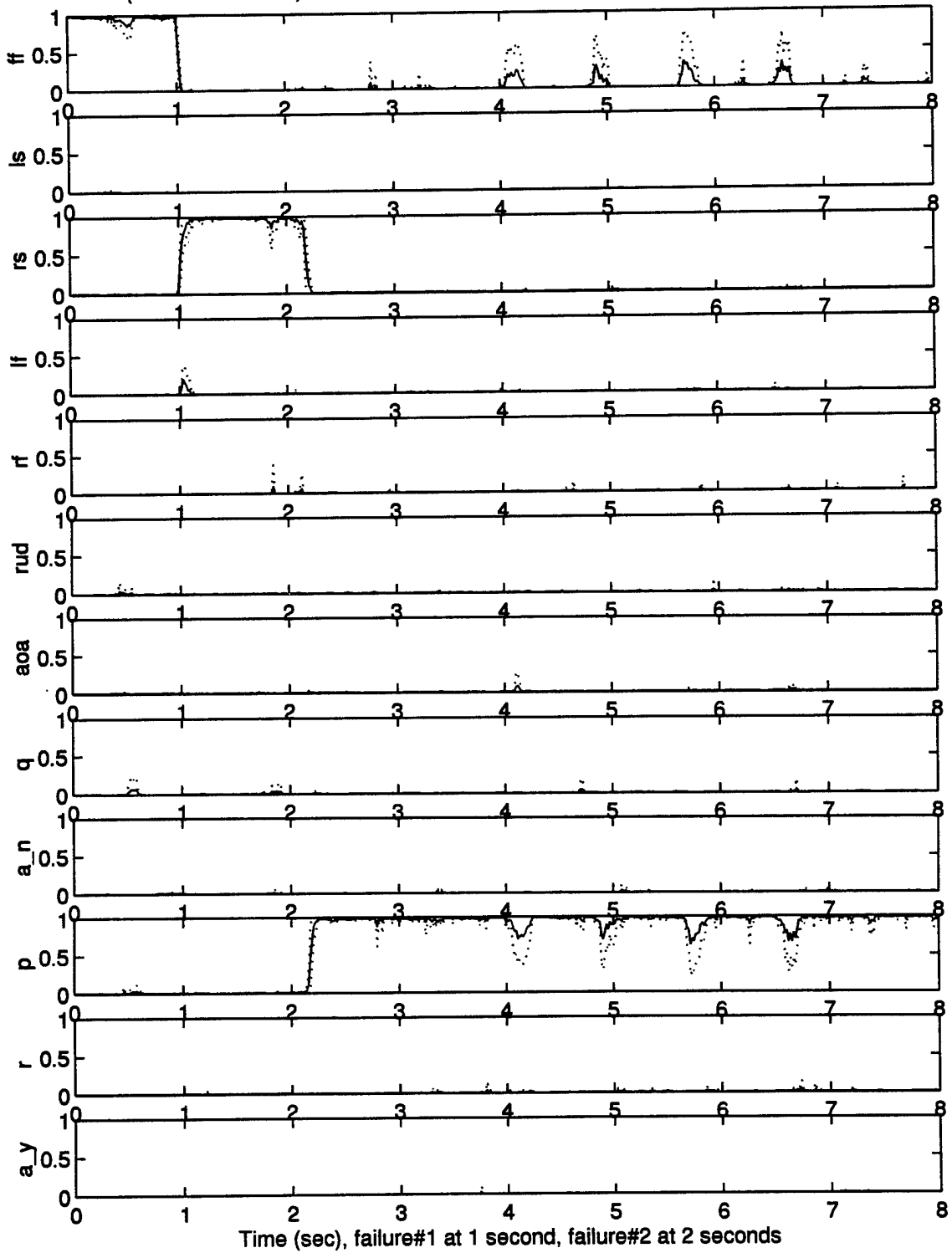


Mean (+/- One Std Dev) Dual-fail Probabilities of fail002.008 with reconfiguration: 10 runs

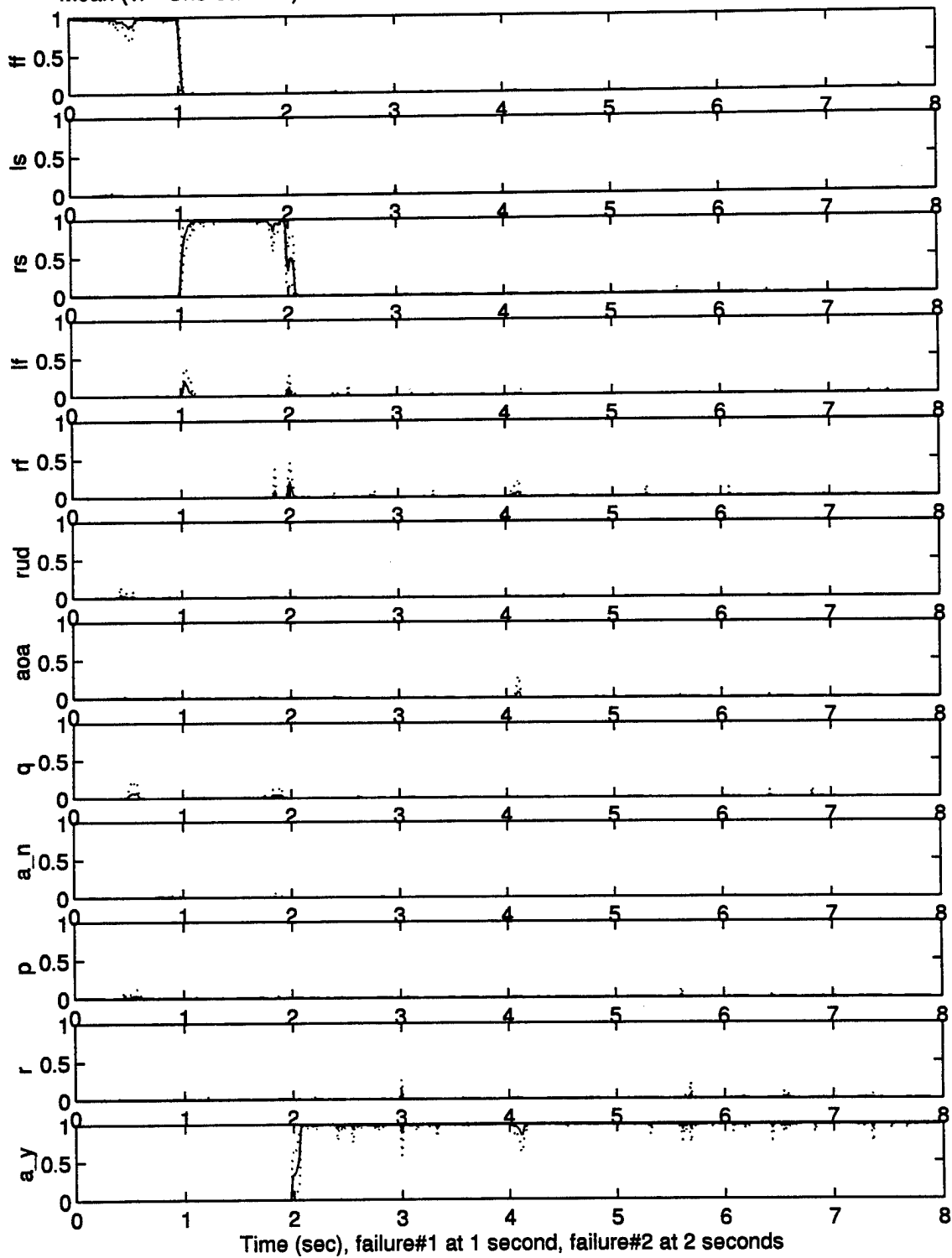


Time (sec), failure#1 at 1 second, failure#2 at 2 seconds

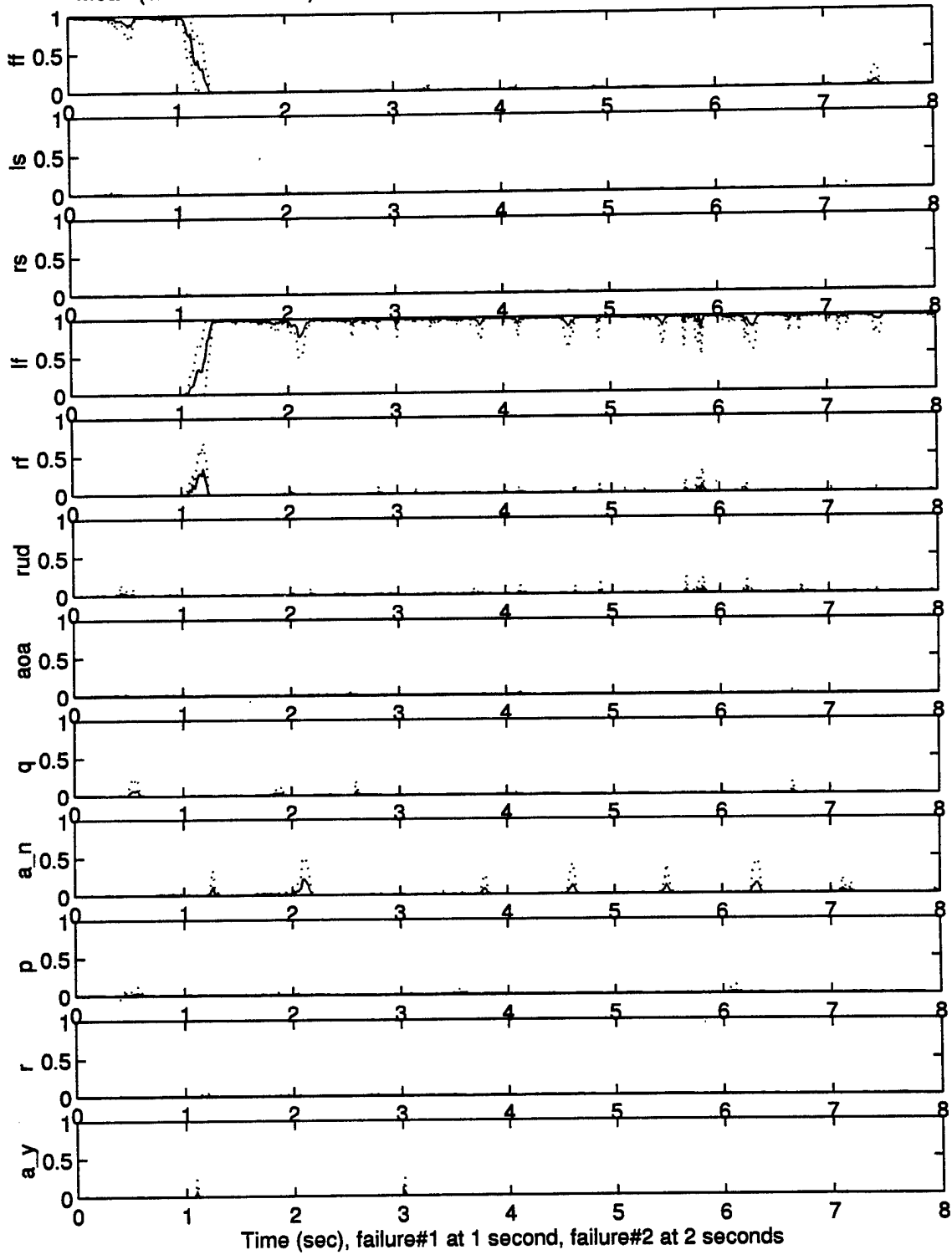
Mean (+/- One Std Dev) Dual-fail Probabilities of fail002.009 with reconfiguration: 10 runs



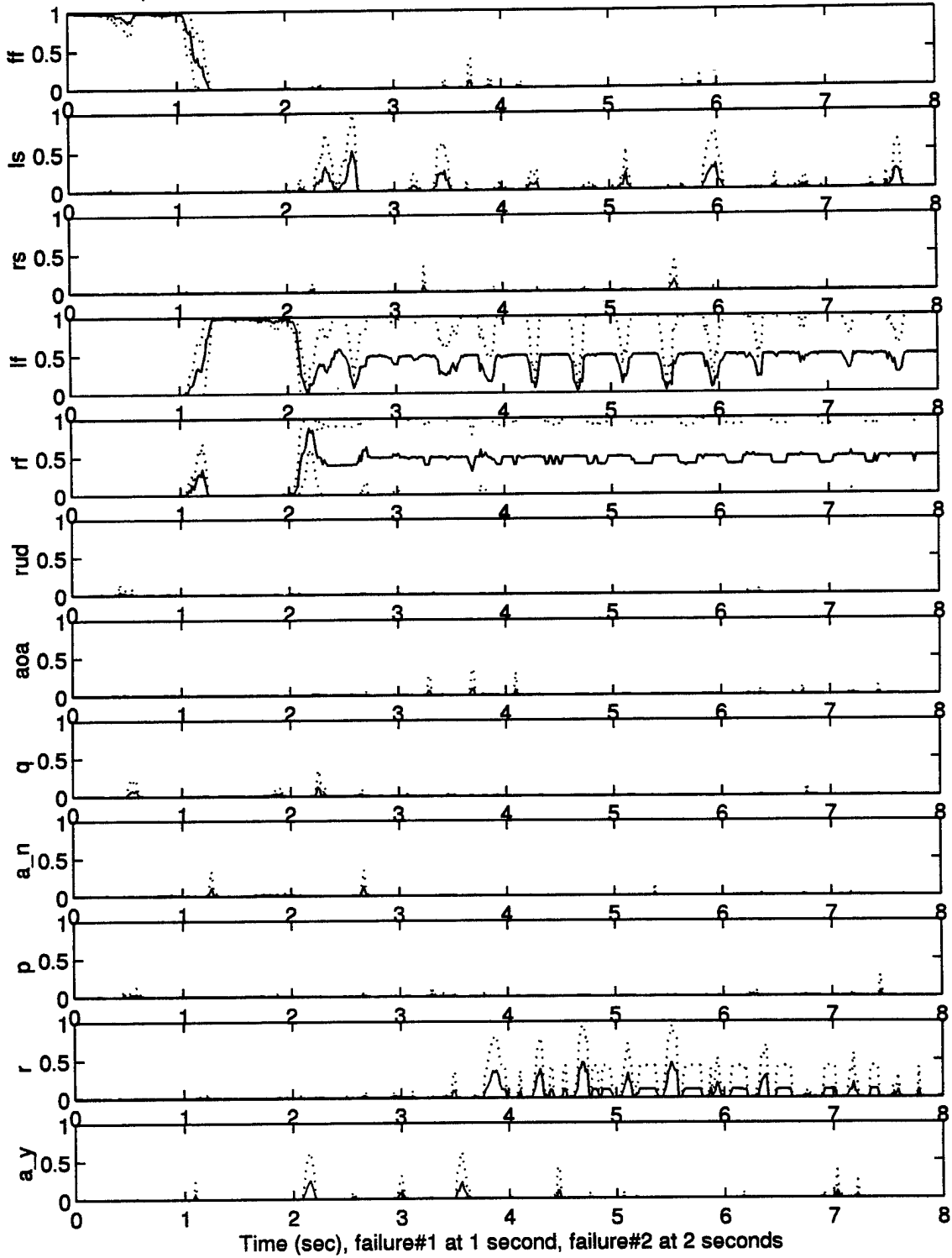
Mean (+/- One Std Dev) Dual-fail Probabilities of fail002.0011 with reconfiguration: 10 runs



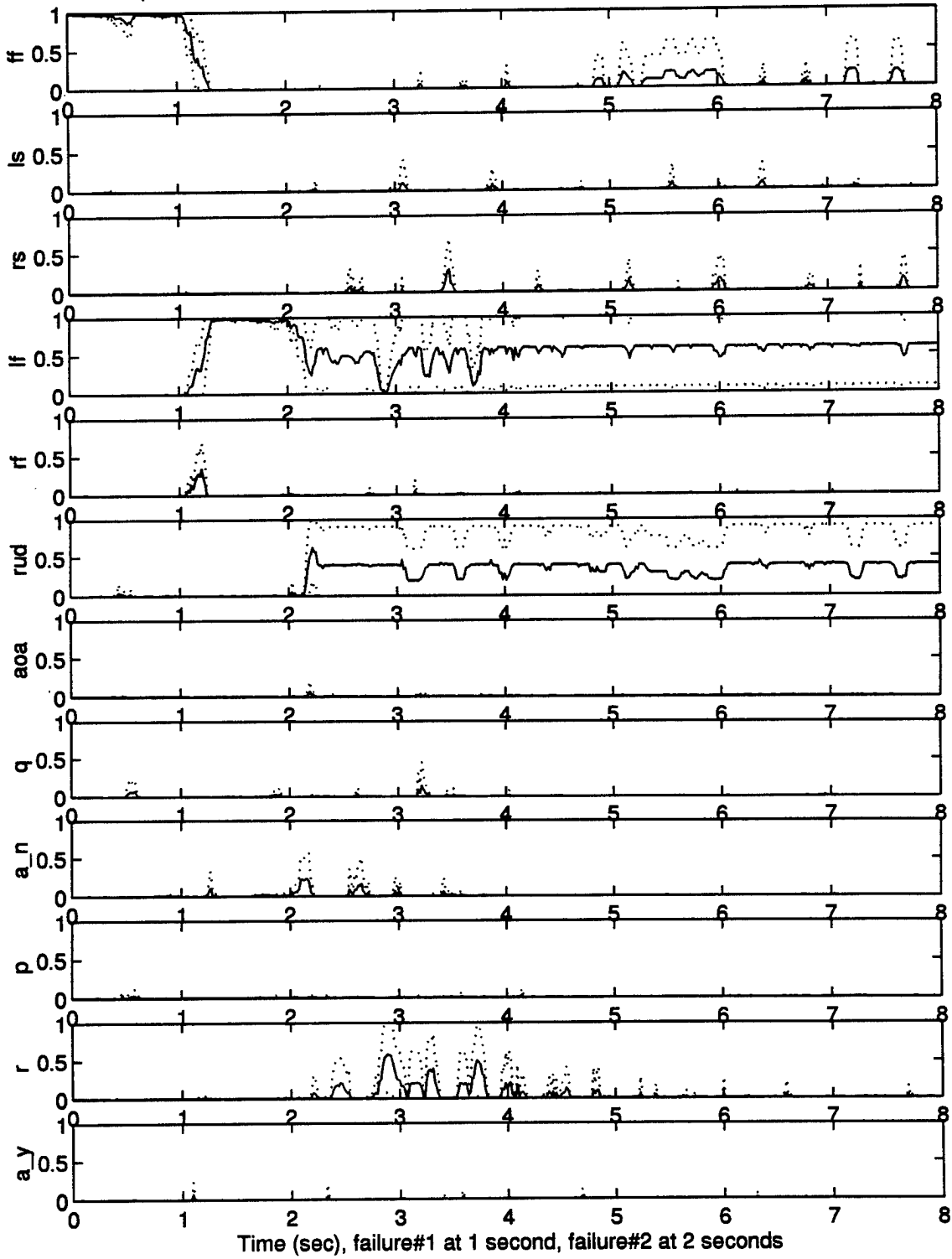
Mean (+/- One Std Dev) Dual-fail Probabilities of fail03.00 with reconfiguration: 10 runs



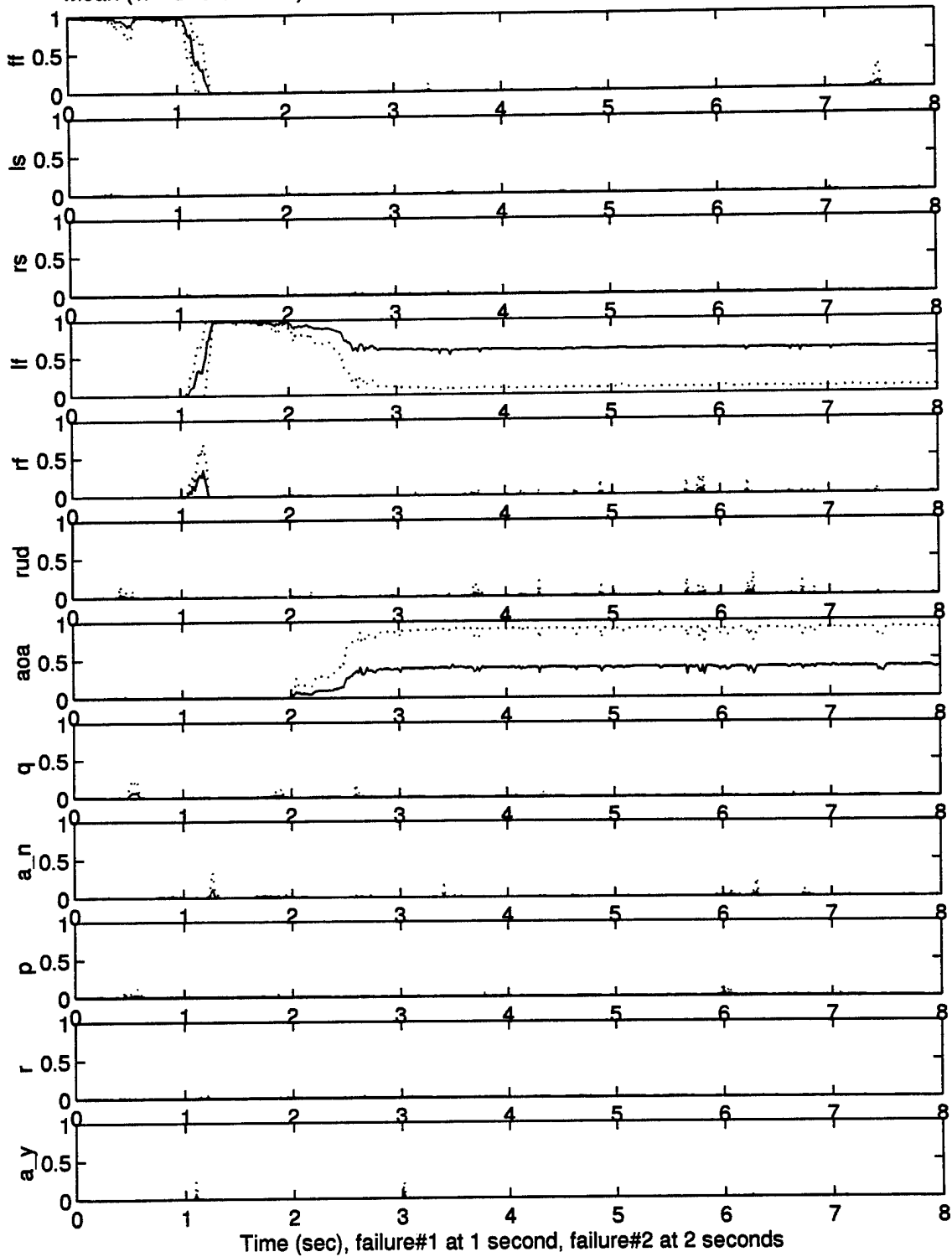
Mean (+/- One Std Dev) Dual-fail Probabilities of fail03.04 with reconfiguration: 10 runs



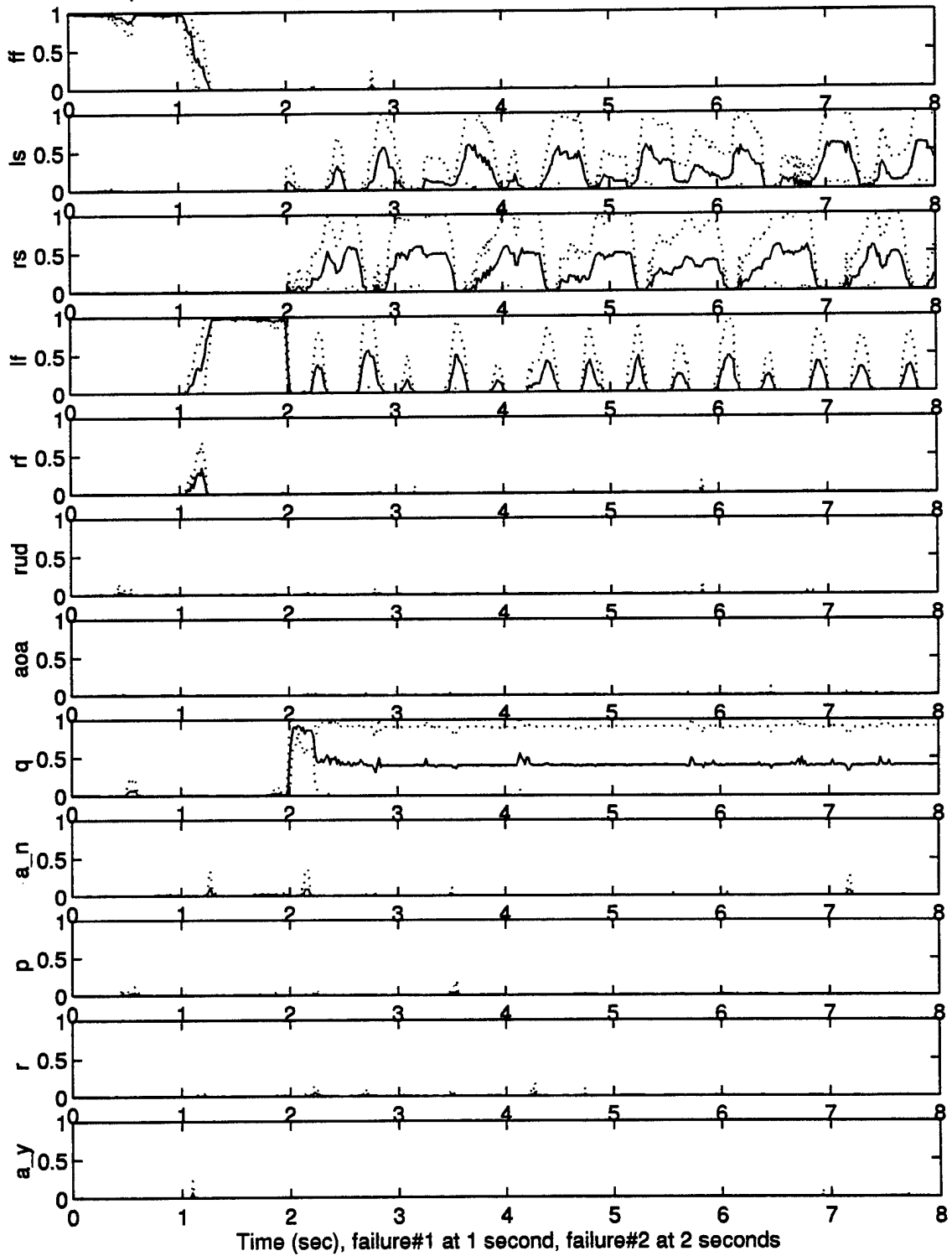
Mean (+/- One Std Dev) Dual-fail Probabilities of fail03.05 with reconfiguration: 10 runs



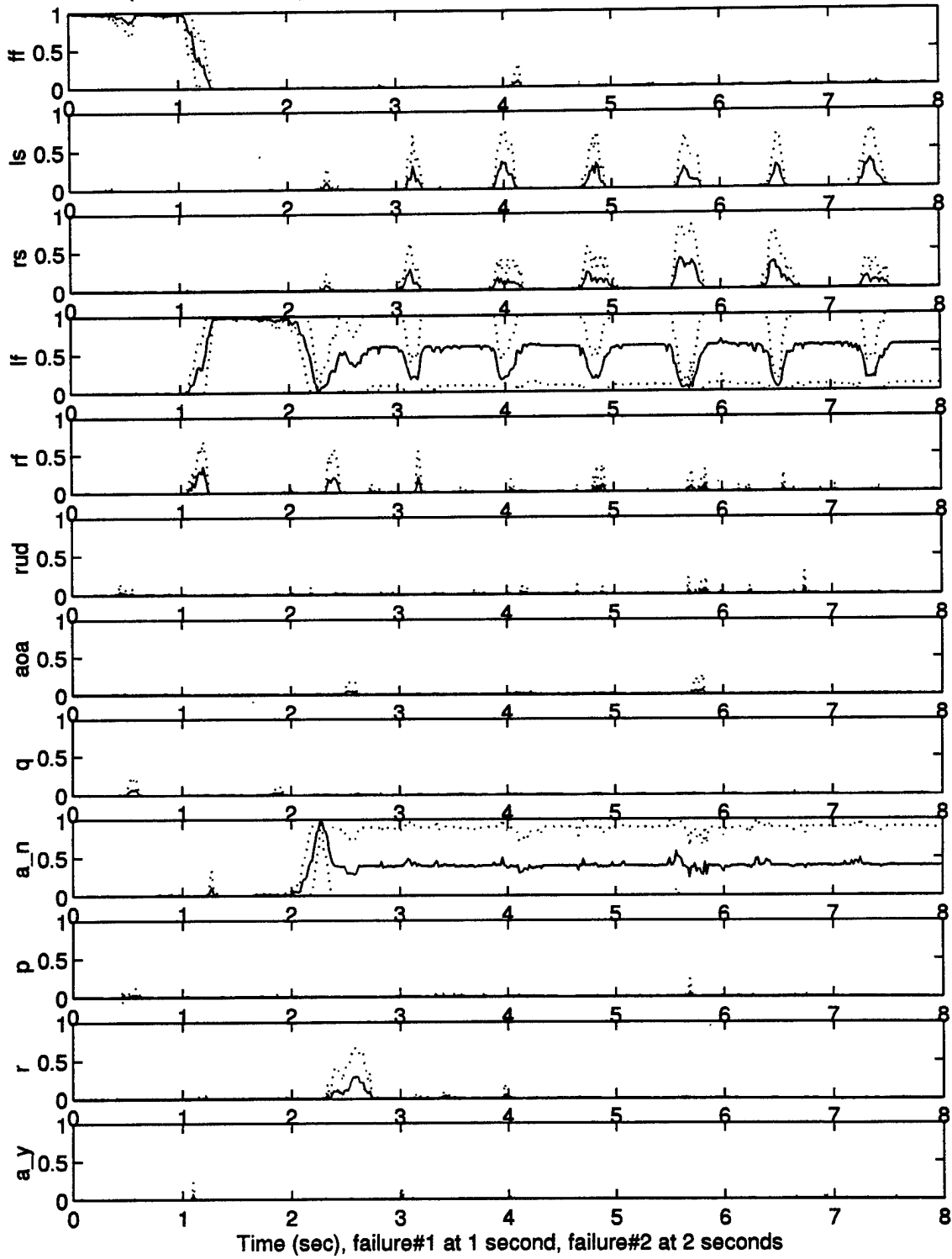
Mean (+/- One Std Dev) Dual-fail Probabilities of fail003.006 with reconfiguration: 10 runs



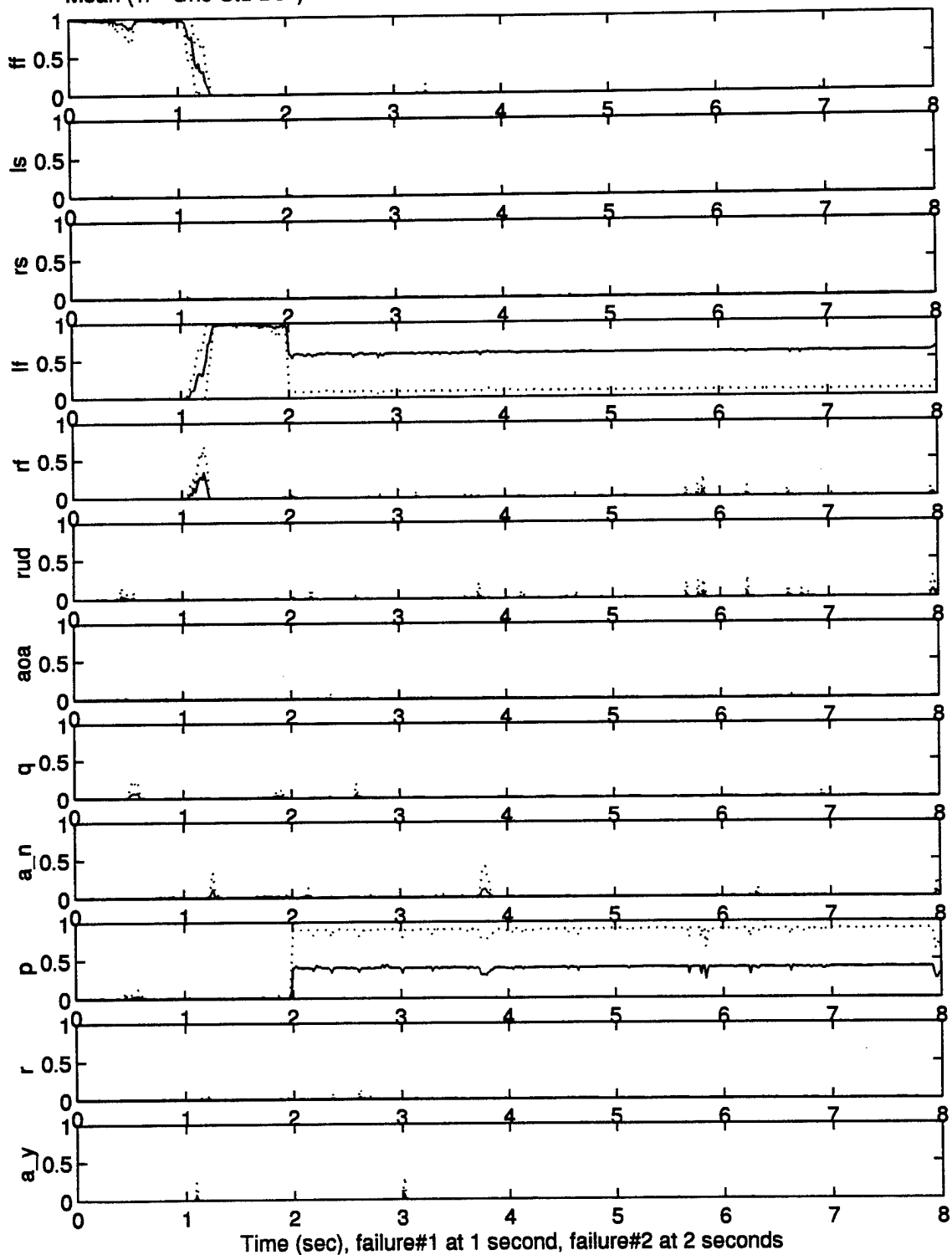
Mean (+/- One Std Dev) Dual-fail Probabilities of fail003.007 with reconfiguration: 10 runs



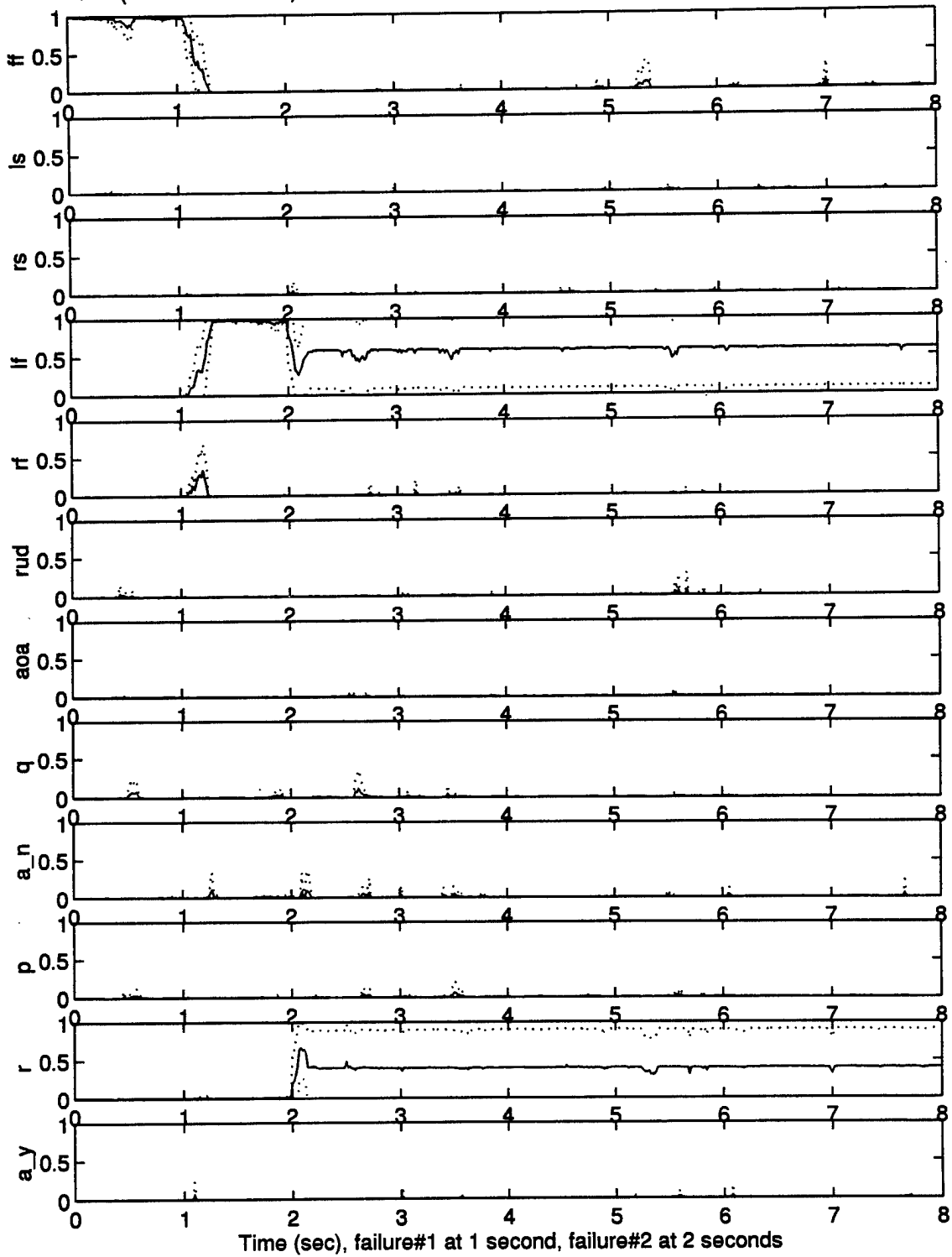
Mean (+/- One Std Dev) Dual-fail Probabilities of fail003.008 with reconfiguration: 10 runs



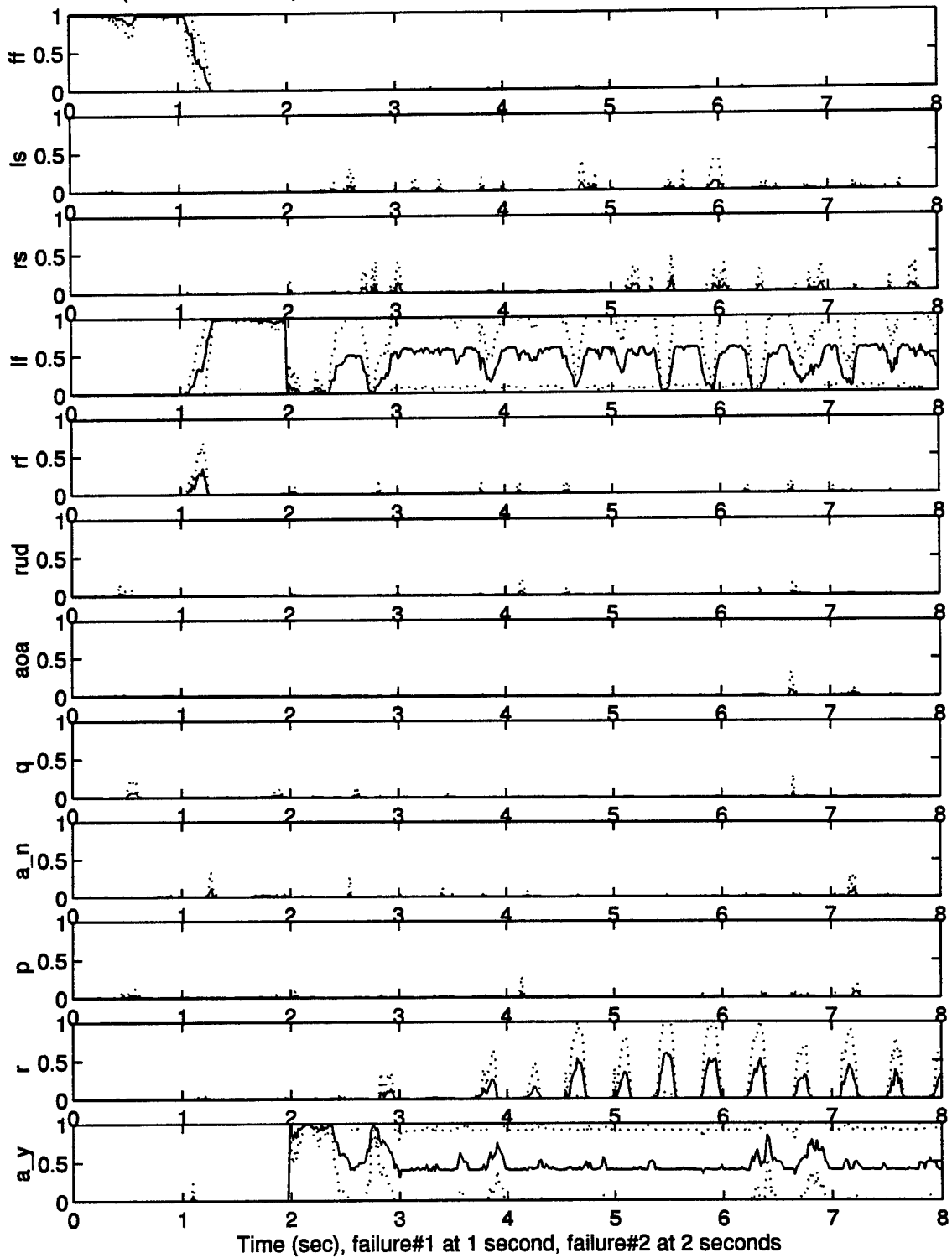
Mean (+/- One Std Dev) Dual-fail Probabilities of fail003.009 with reconfiguration: 10 runs



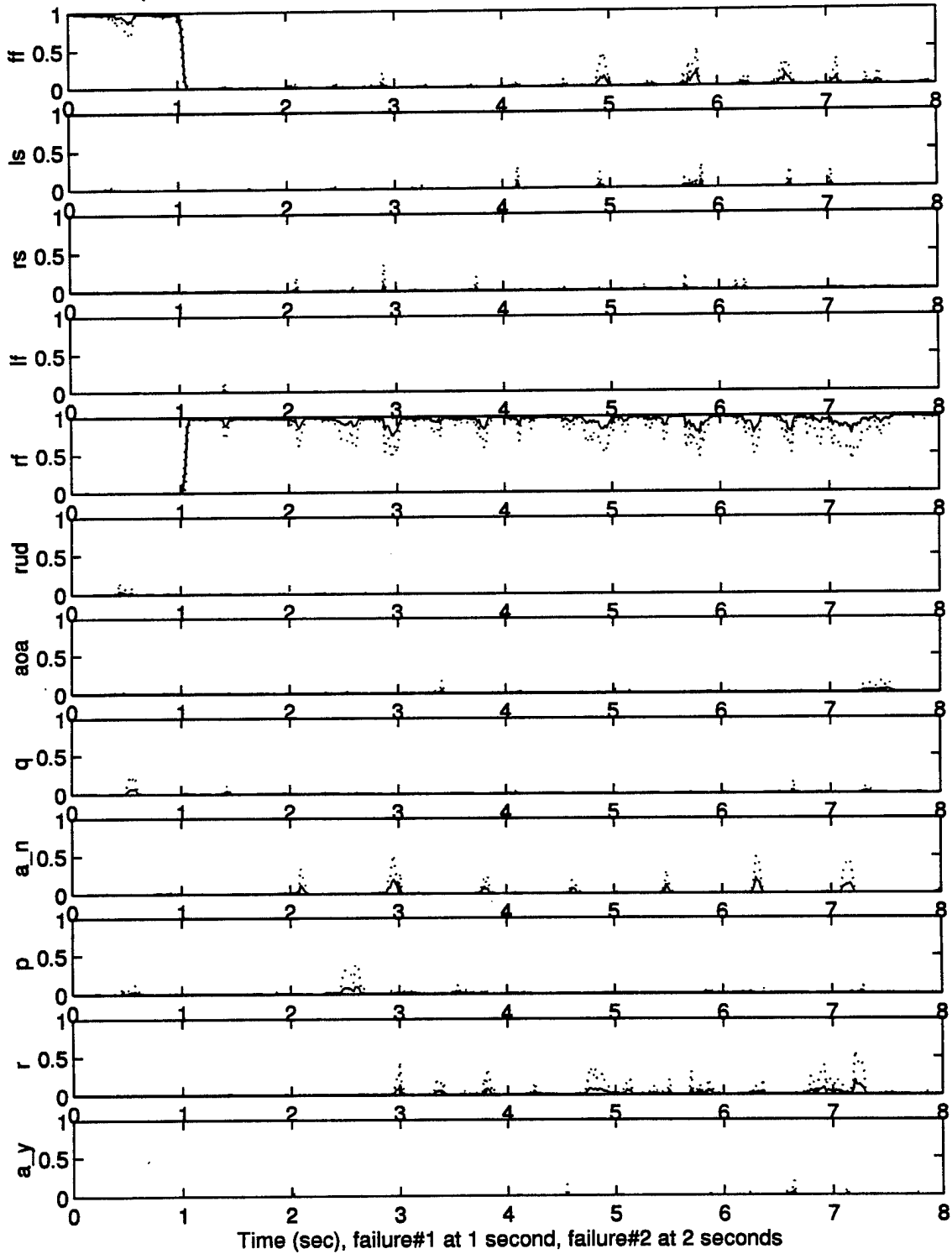
Mean (+/- One Std Dev) Dual-fail Probabilities of fail003.0010 with reconfiguration: 10 runs



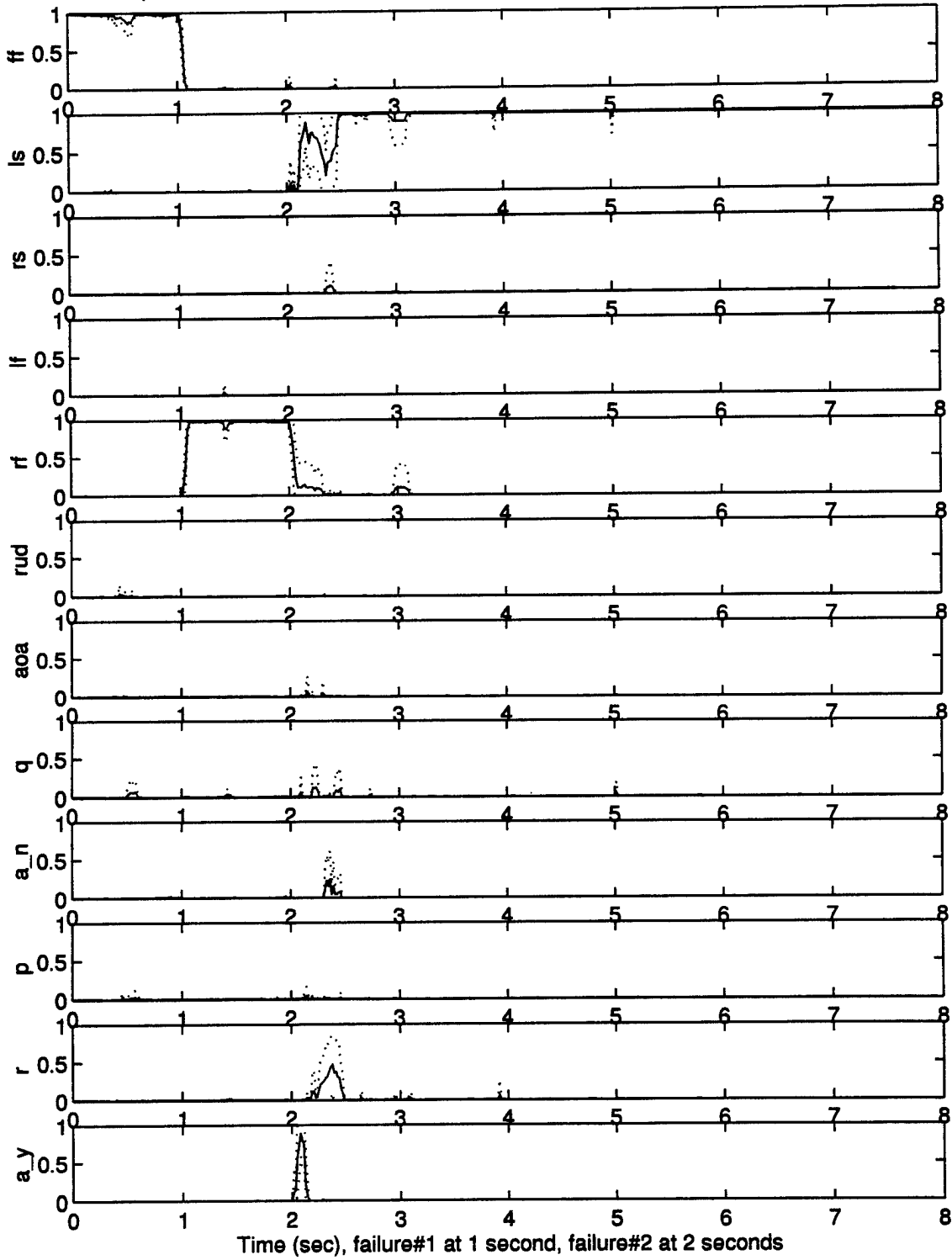
Mean (+/- One Std Dev) Dual-fail Probabilities of fail003.0011 with reconfiguration: 10 runs



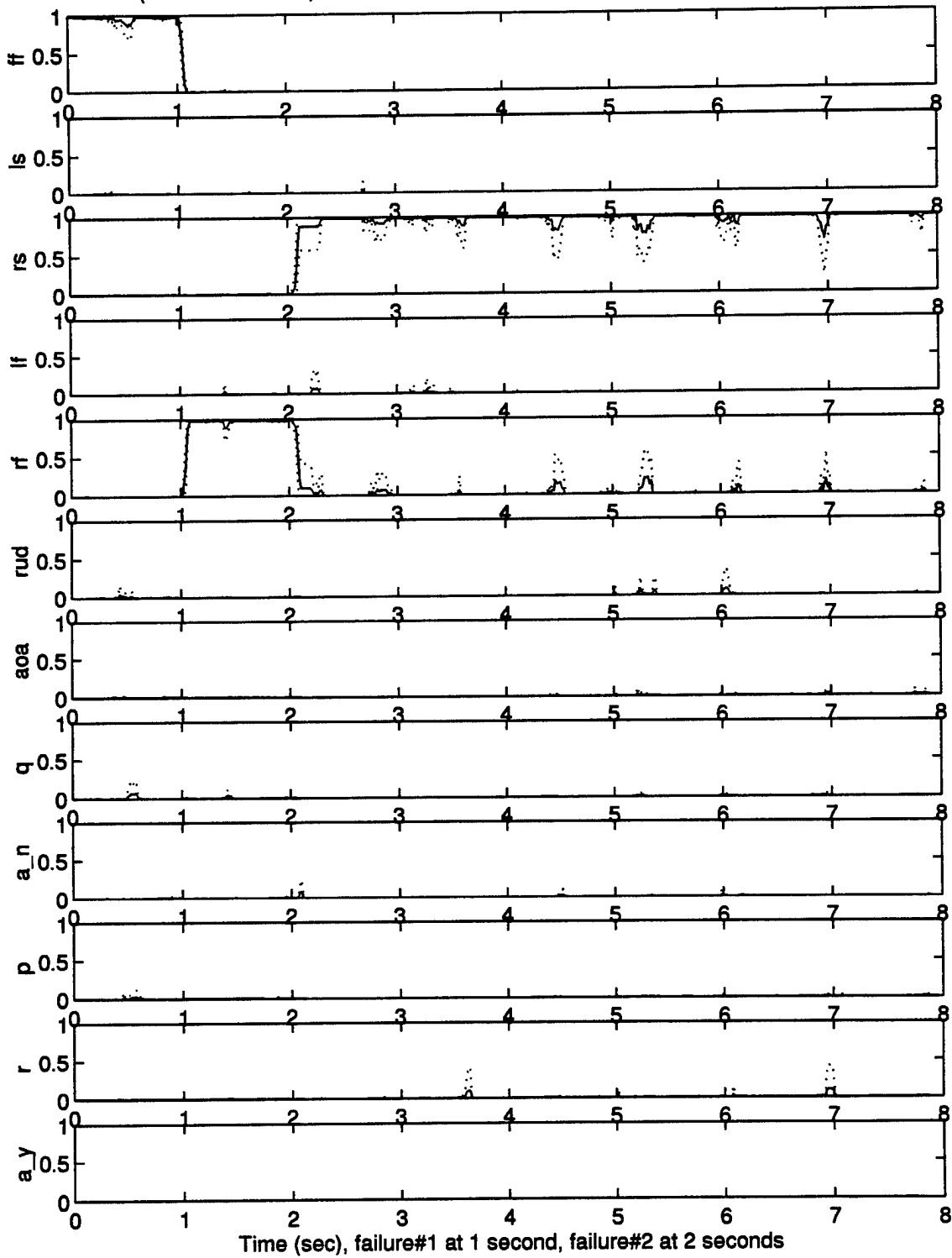
Mean (+/- One Std Dev) Dual-fail Probabilities of fail04.00 with reconfiguration: 10 runs



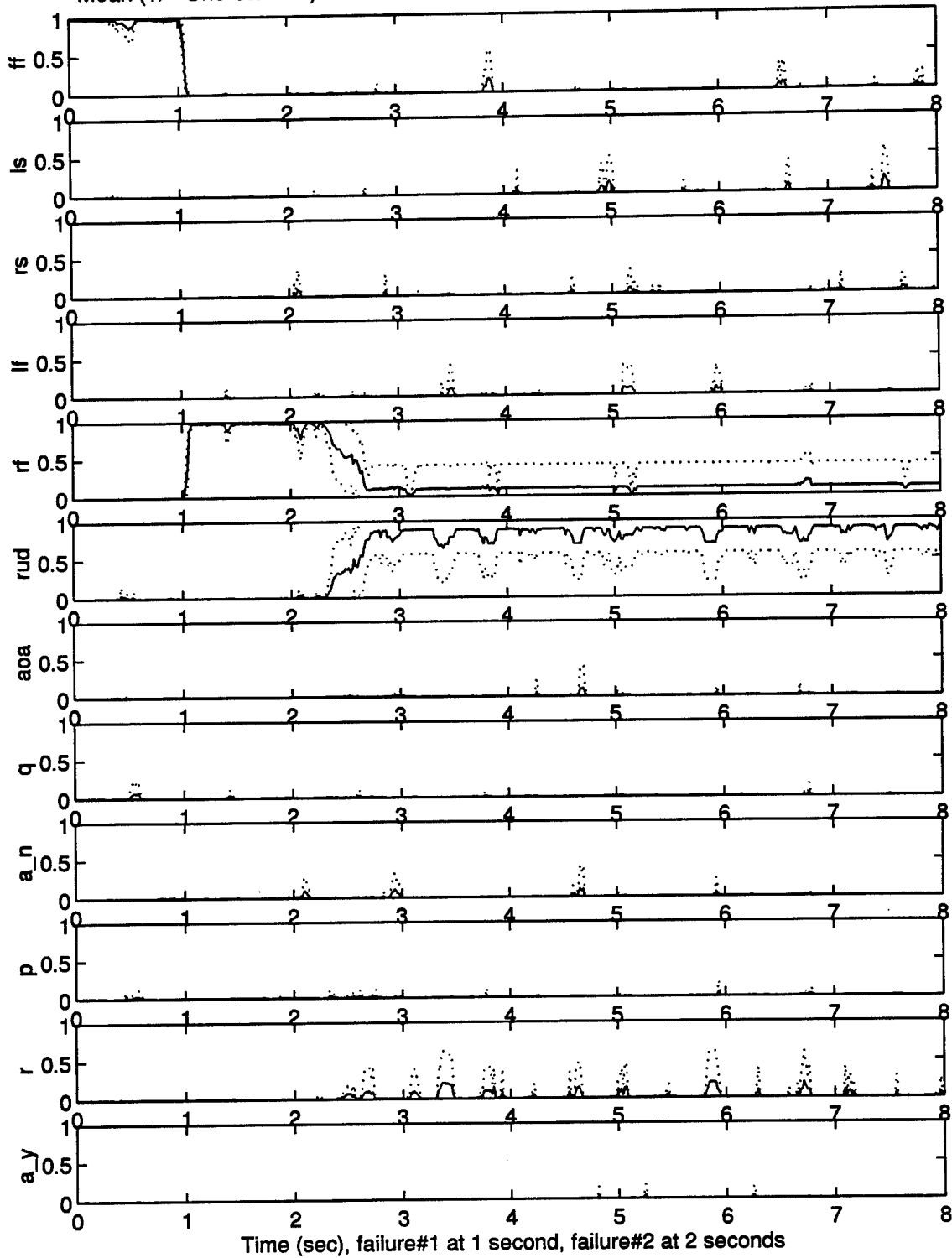
Mean (+/- One Std Dev) Dual-fail Probabilities of fail04.01 with reconfiguration: 10 runs



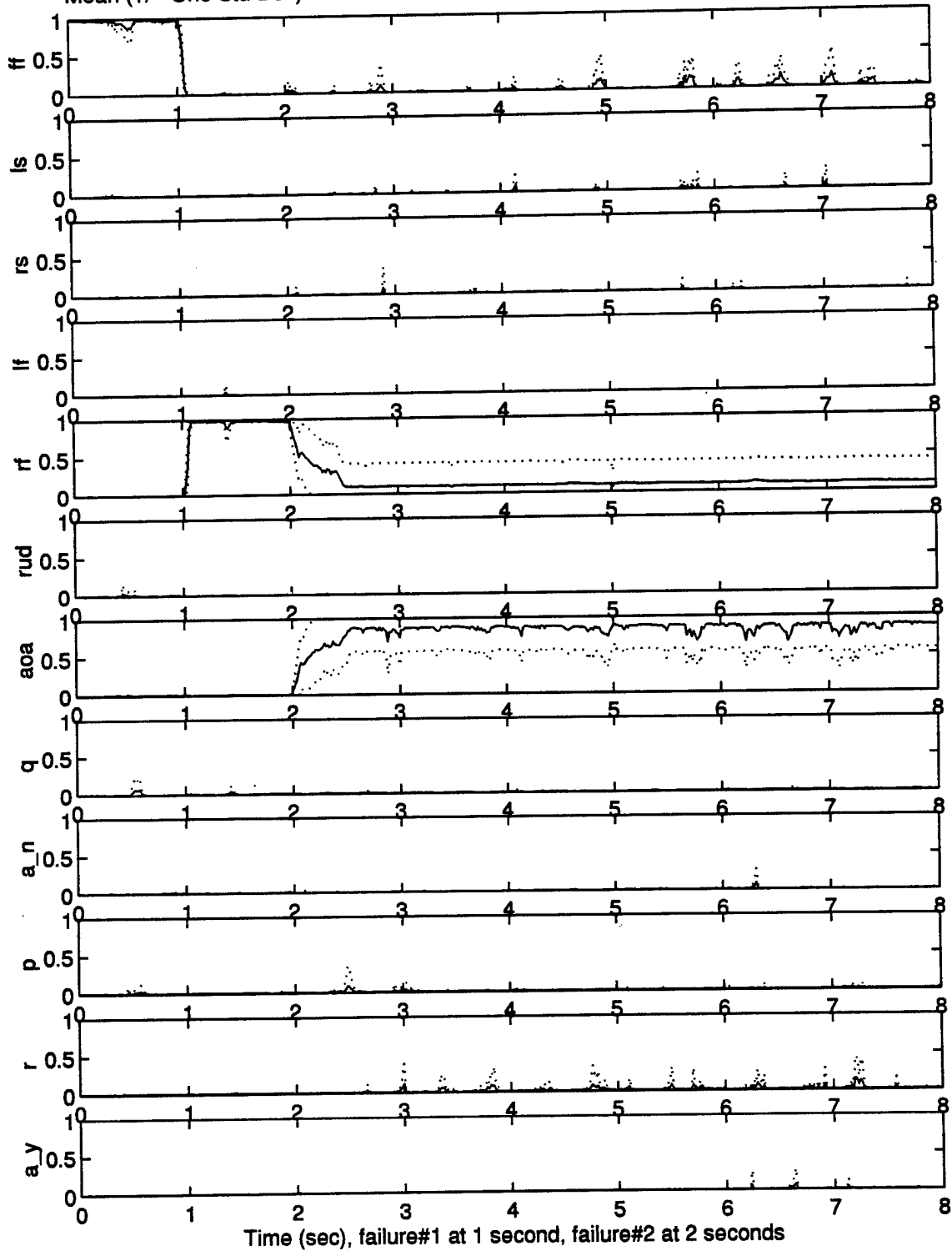
Mean (+/- One Std Dev) Dual-fail Probabilities of fail04.02 with reconfiguration: 10 runs



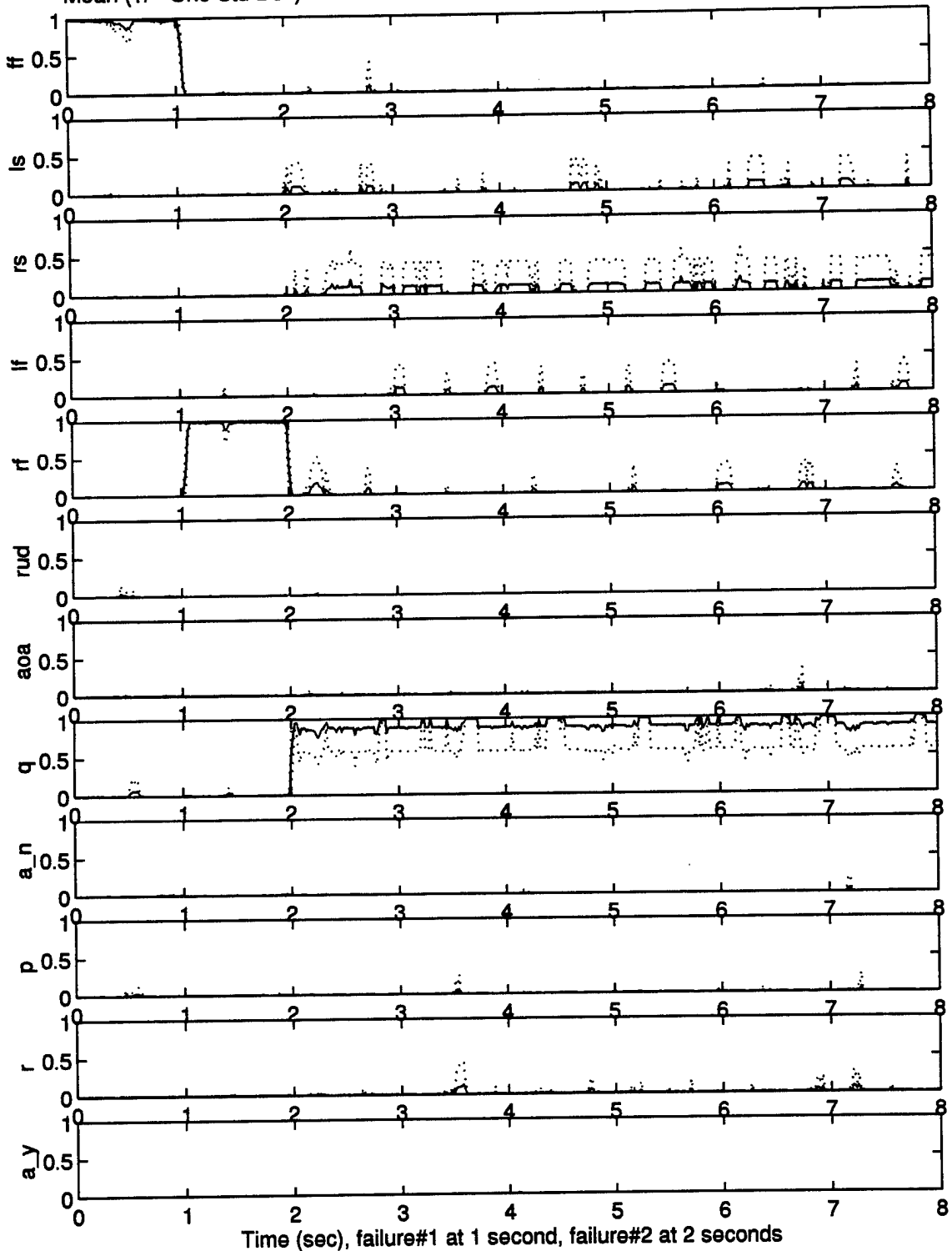
Mean (+/- One Std Dev) Dual-fail Probabilities of fail04.05 with reconfiguration: 10 runs



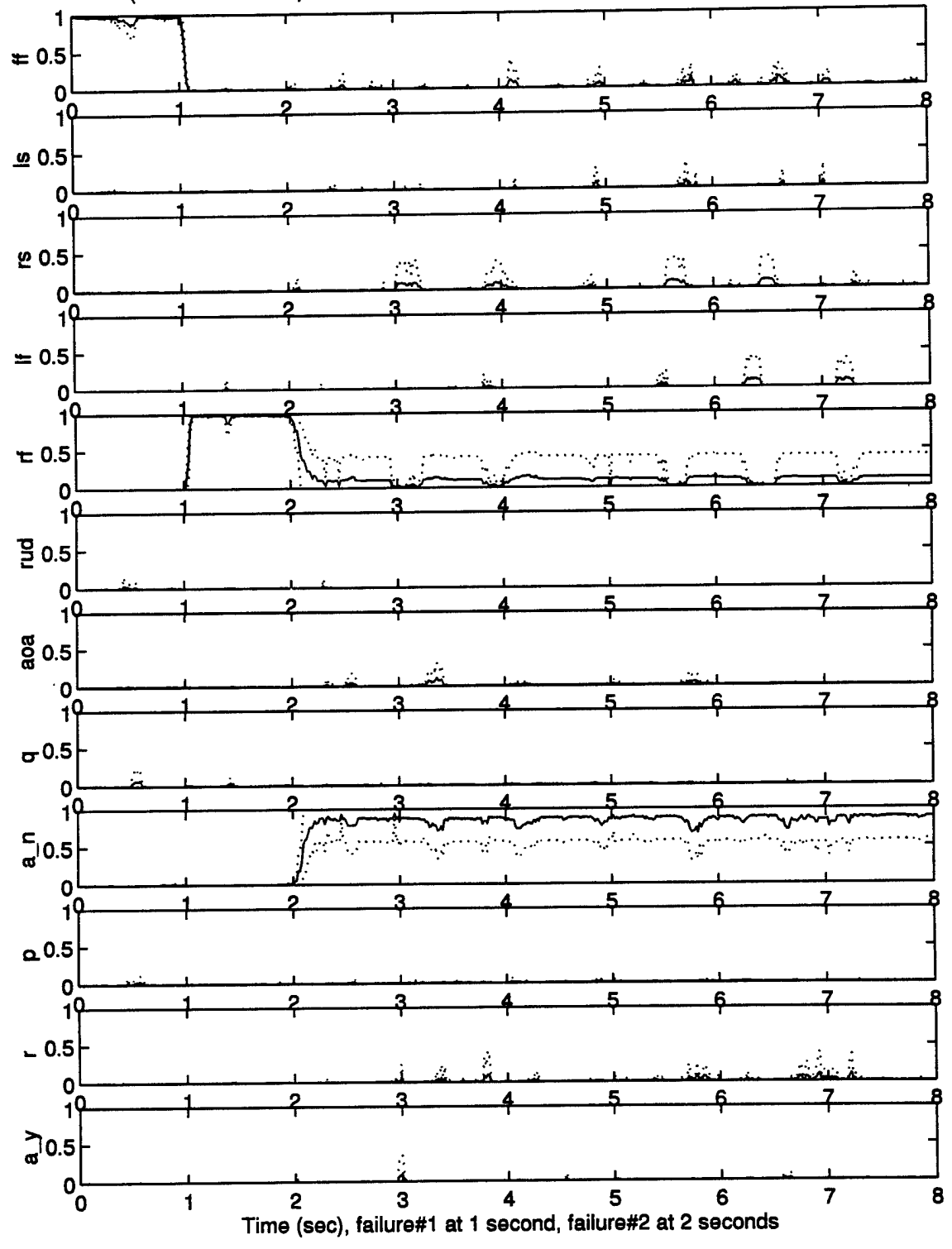
Mean (+/- One Std Dev) Dual-fail Probabilities of fail004.006 with reconfiguration: 10 runs



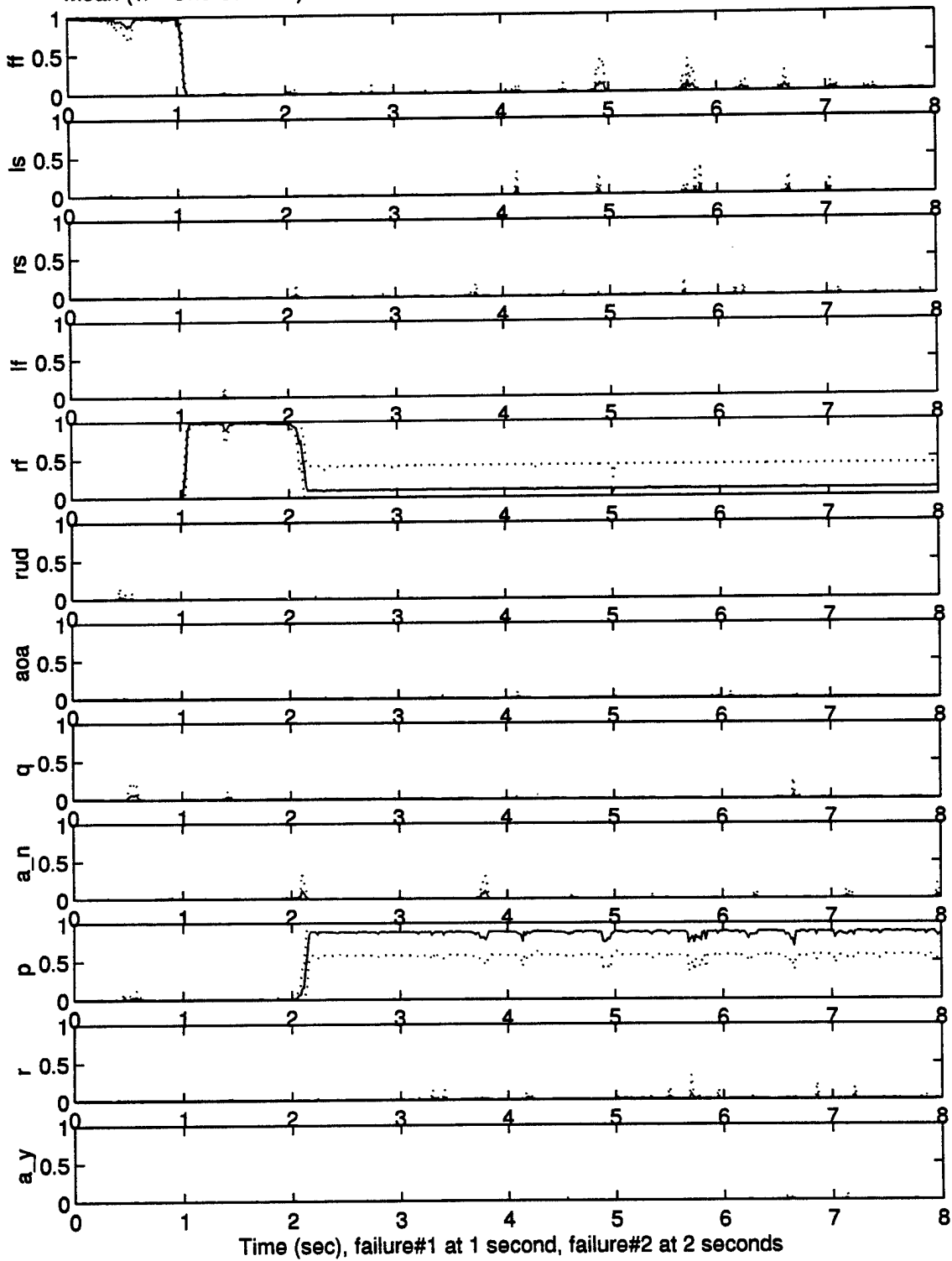
Mean (+/- One Std Dev) Dual-fail Probabilities of fail004.007 with reconfiguration: 10 runs



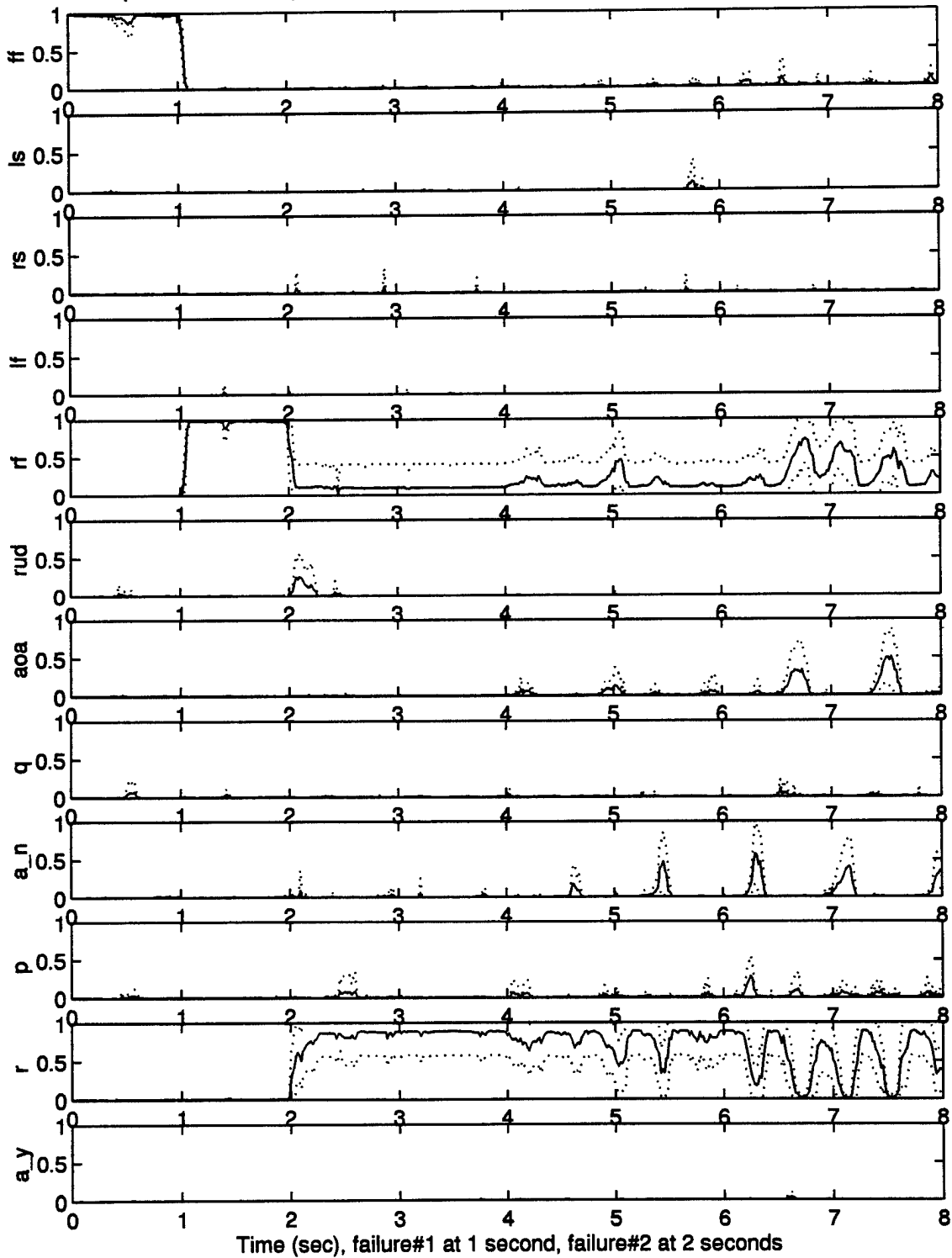
Mean (+/- One Std Dev) Dual-fail Probabilities of fail004.008 with reconfiguration: 10 runs



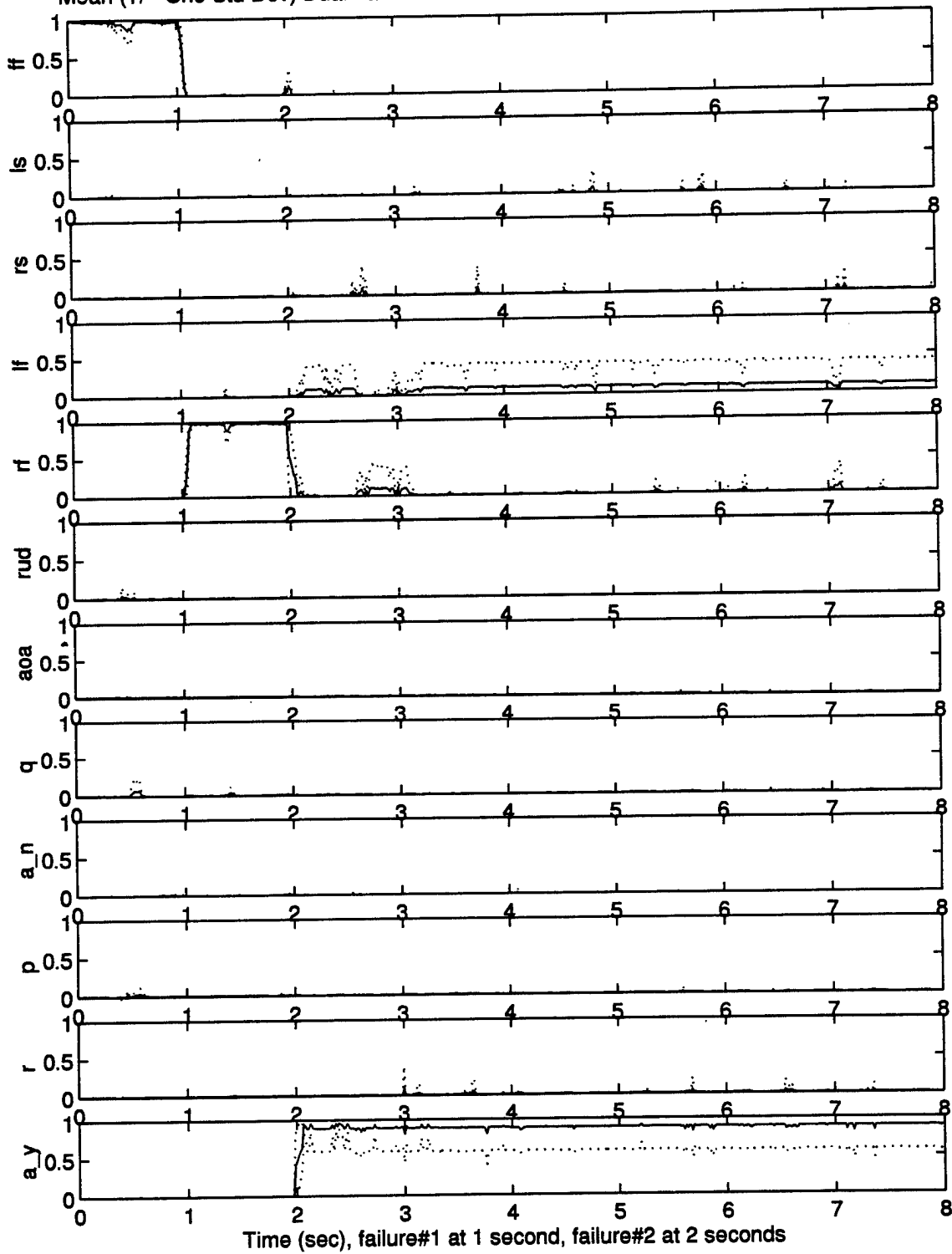
Mean (+/- One Std Dev) Dual-fail Probabilities of fail004.009 with reconfiguration: 10 runs



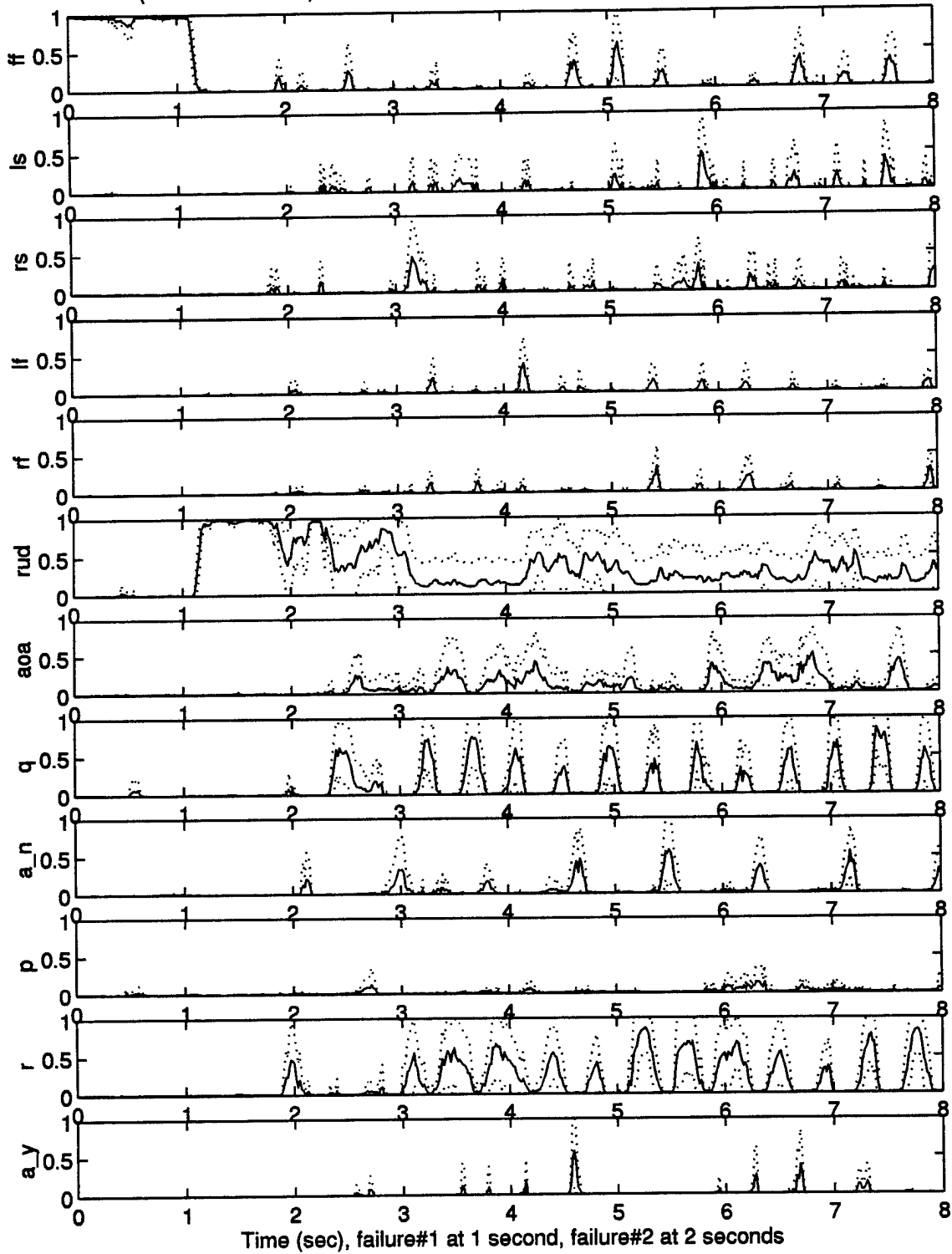
Mean (+/- One Std Dev) Dual-fail Probabilities of fail004.0010 with reconfiguration: 10 runs



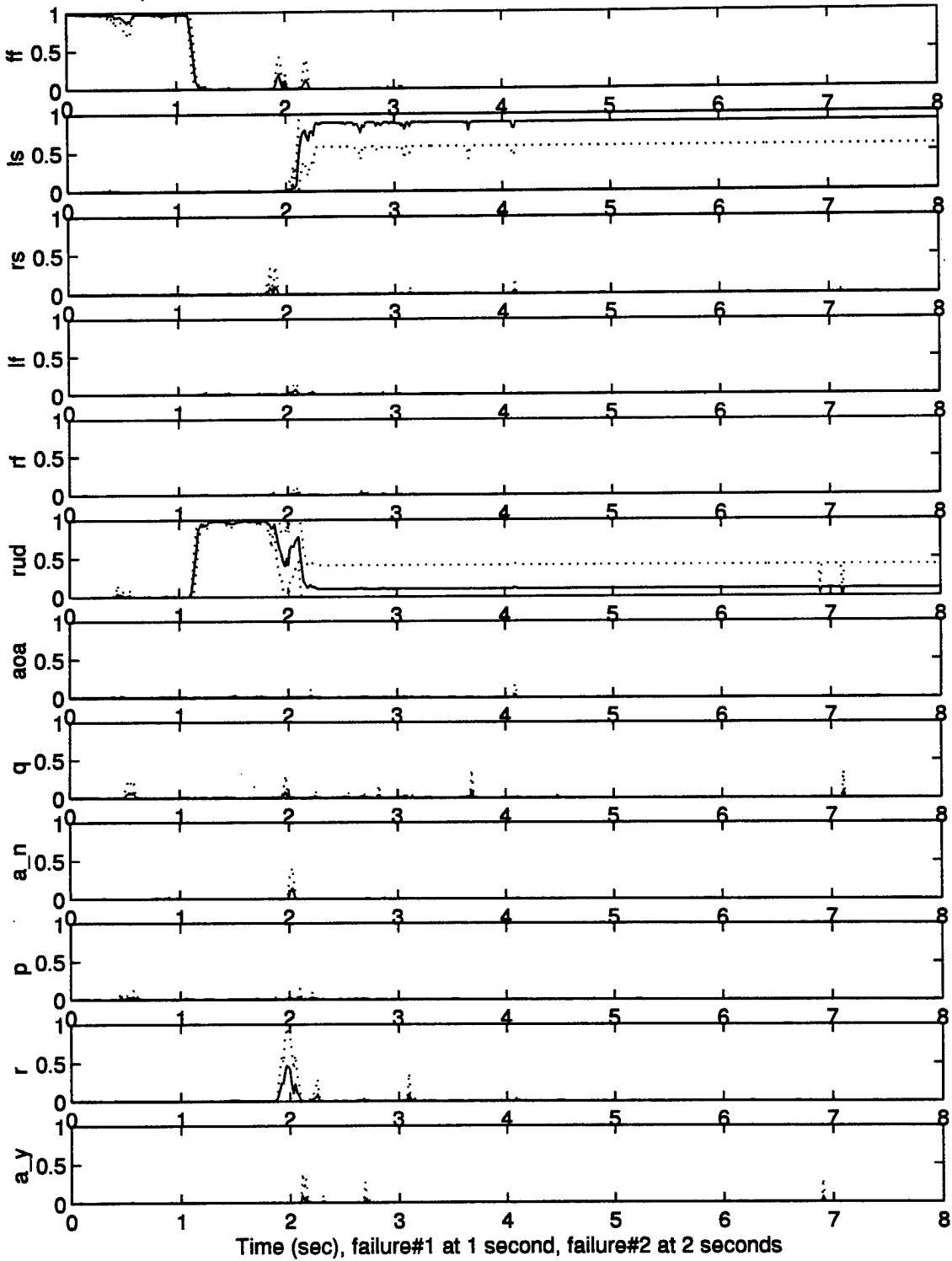
Mean (+/- One Std Dev) Dual-fail Probabilities of fail004.0011 with reconfiguration: 10 runs



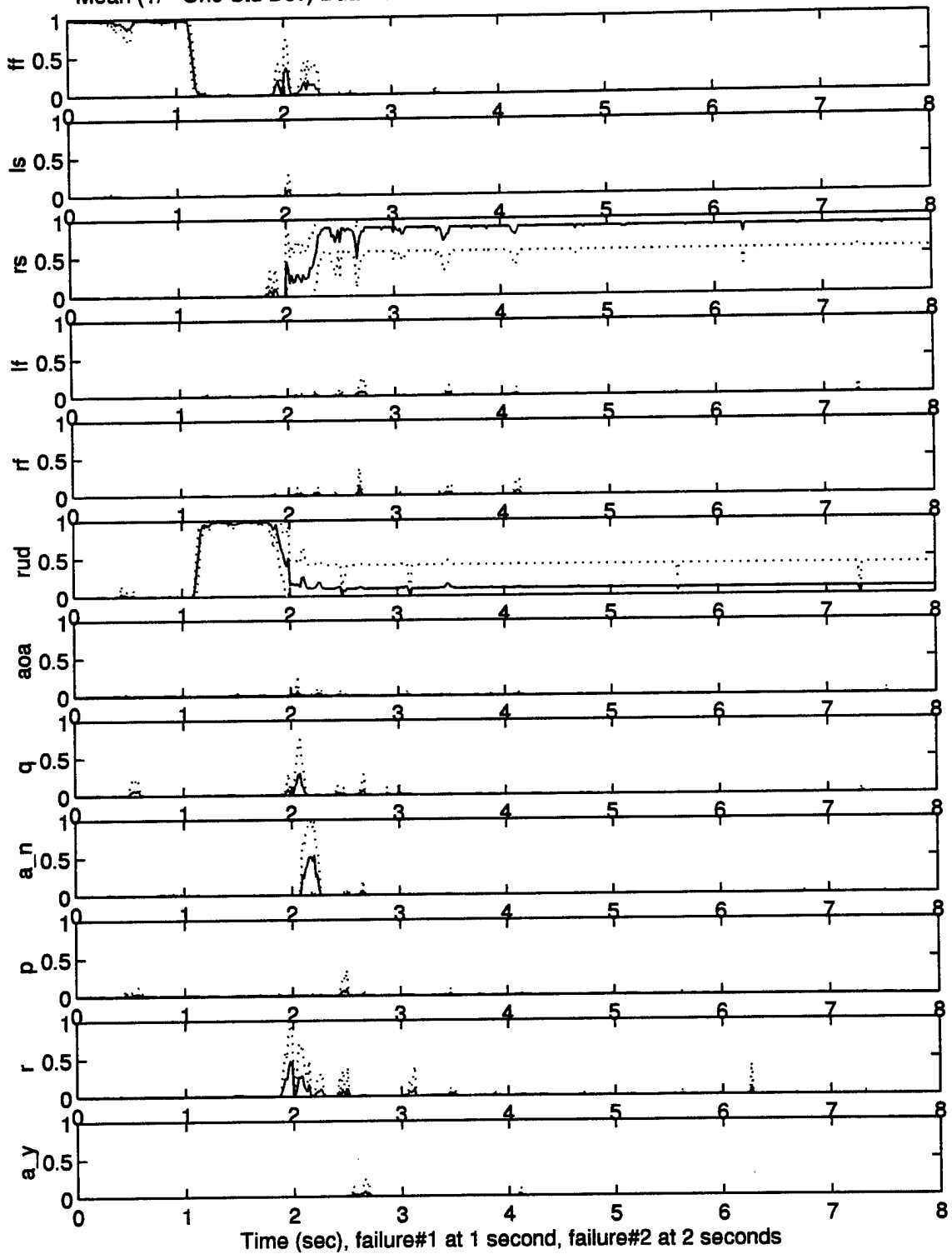
Mean (+/- One Std Dev) Dual-fail Probabilities of fail05.00 with reconfiguration: 10 runs



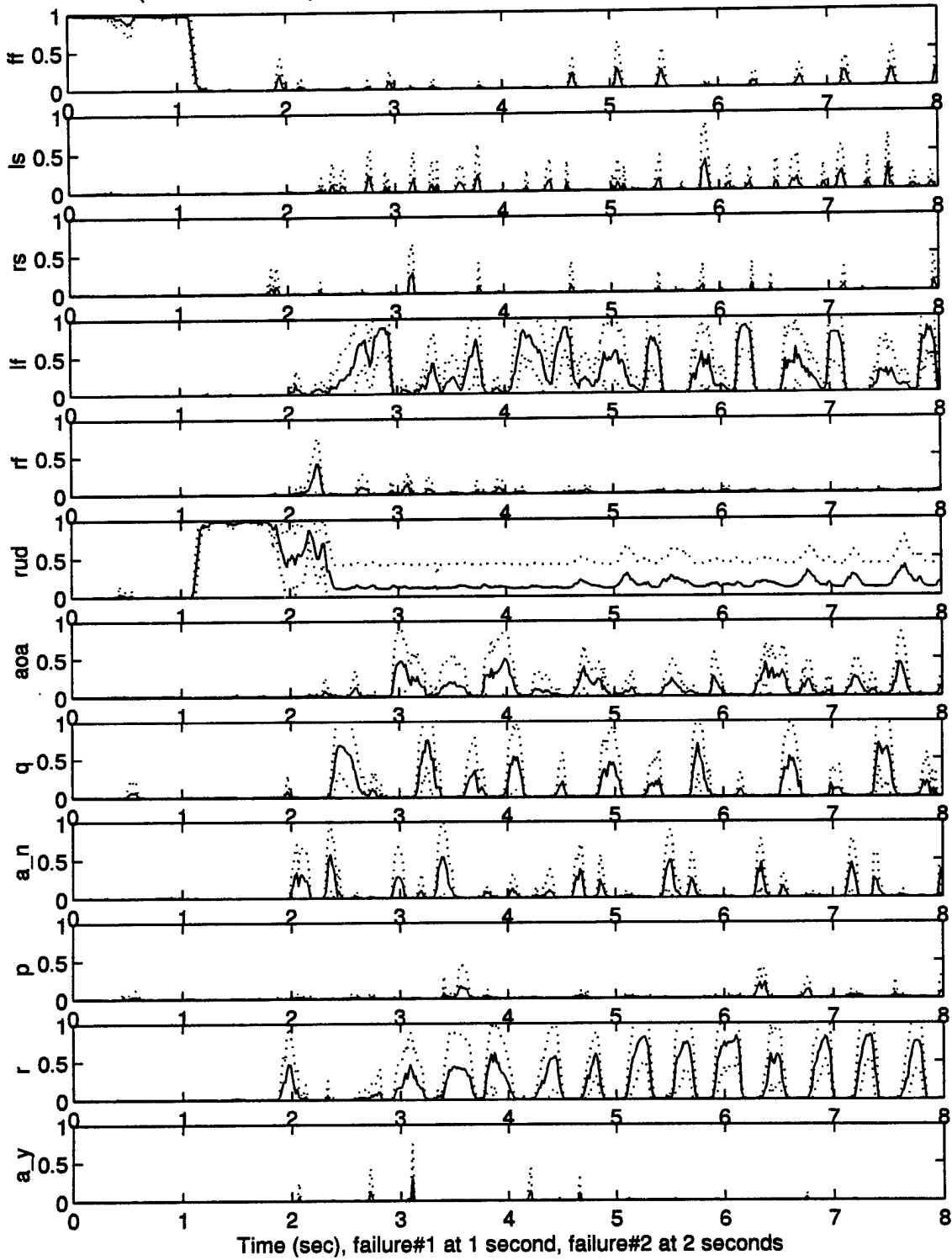
Mean (+/- One Std Dev) Dual-fail Probabilities of fail05.01 with reconfiguration: 10 runs



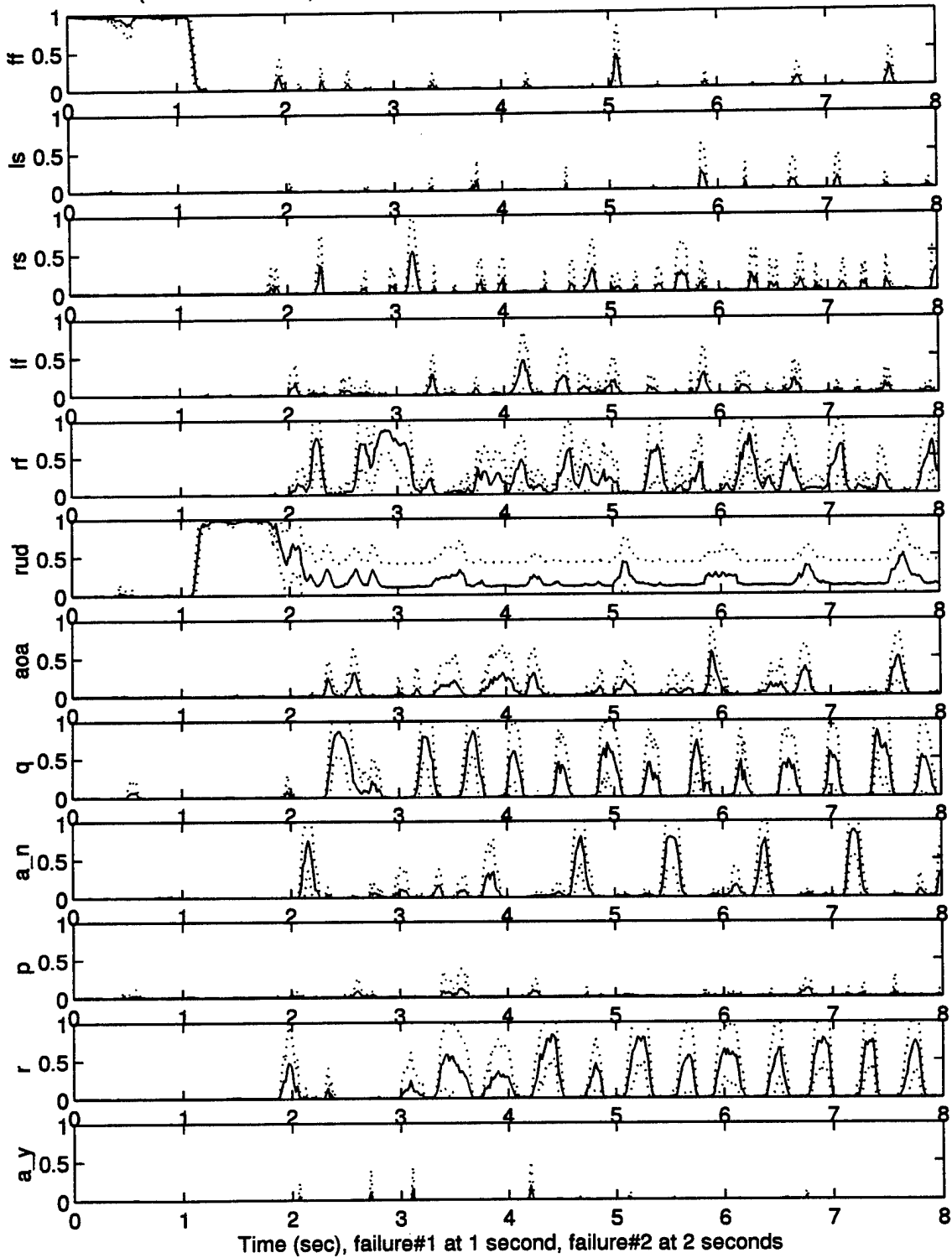
Mean (+/- One Std Dev) Dual-fail Probabilities of fail05.02 with reconfiguration: 10 runs



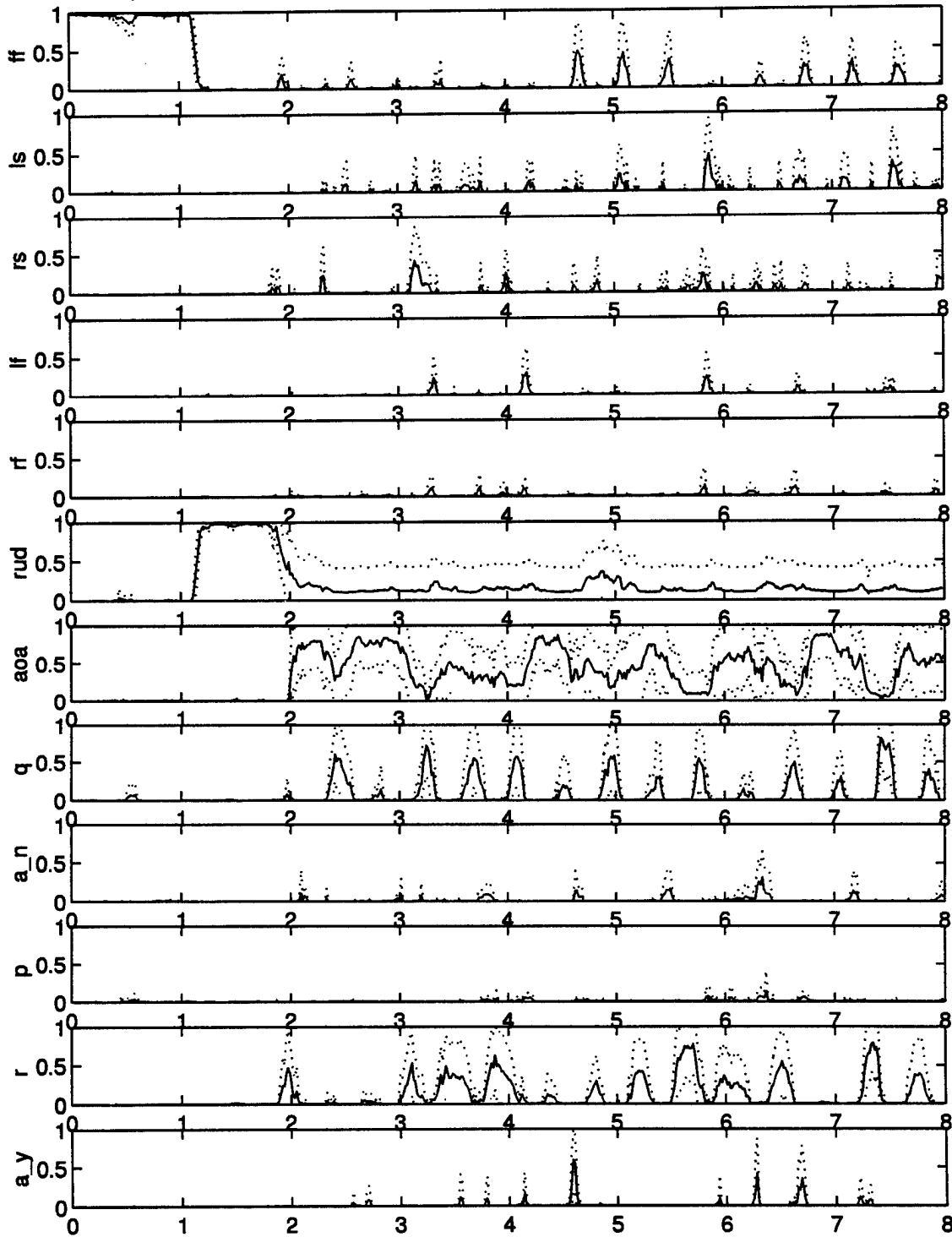
Mean (+/- One Std Dev) Dual-fail Probabilities of fail05.03 with reconfiguration: 10 runs



Mean (+/- One Std Dev) Dual-fail Probabilities of fail05.04 with reconfiguration: 10 runs

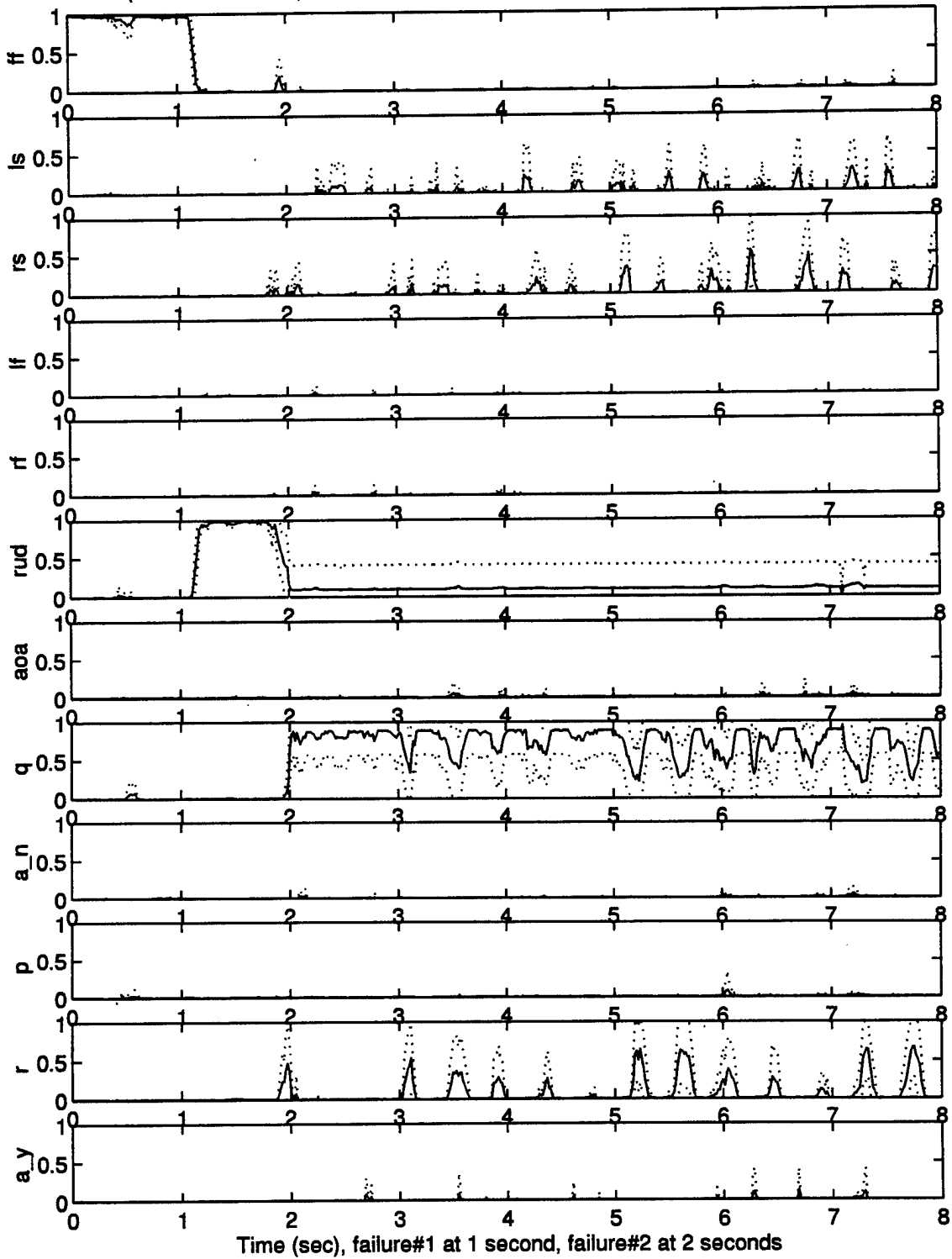


Mean (+/- One Std Dev) Dual-fail Probabilities of fail005.006 with reconfiguration: 10 runs

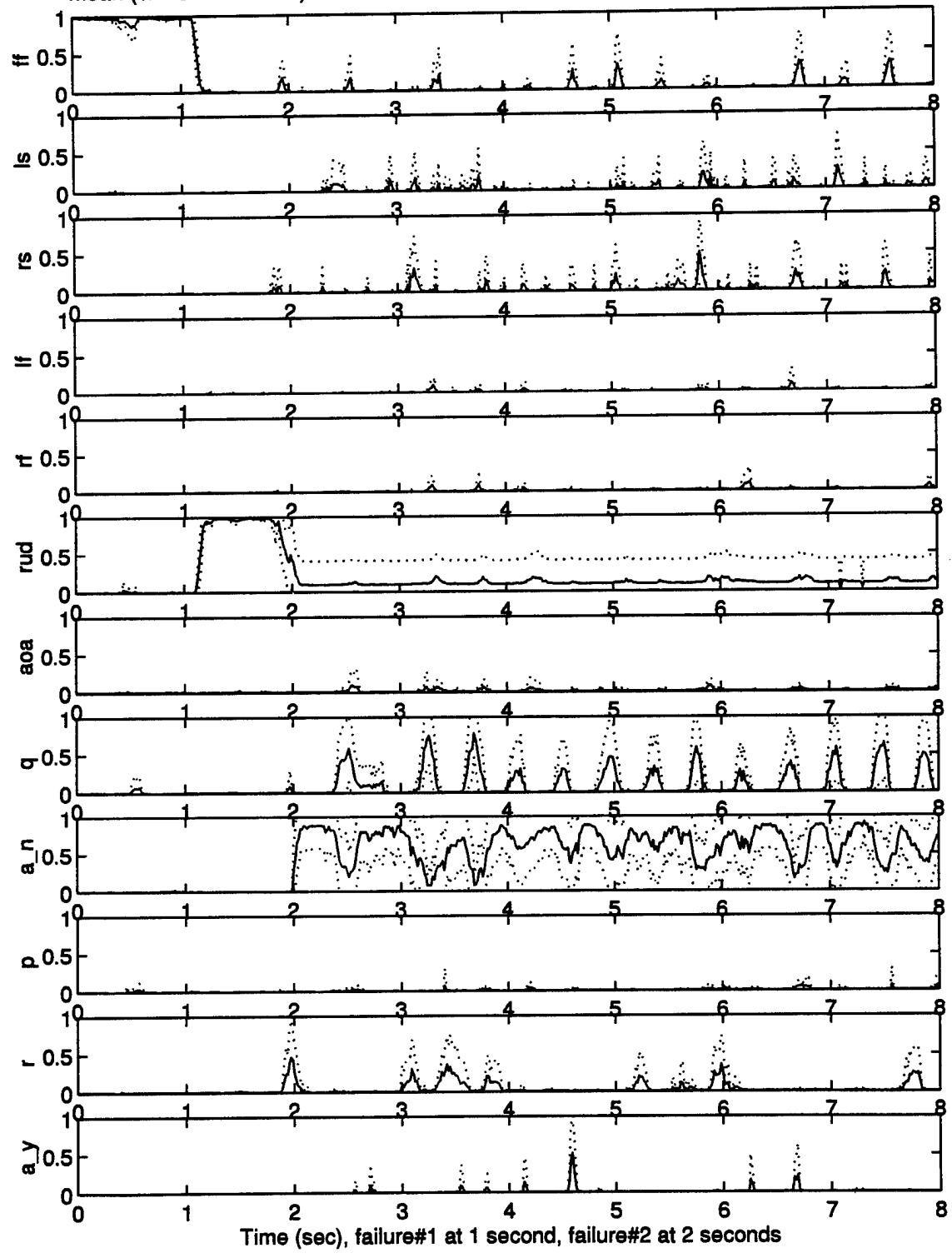


Time (sec), failure#1 at 1 second, failure#2 at 2 seconds

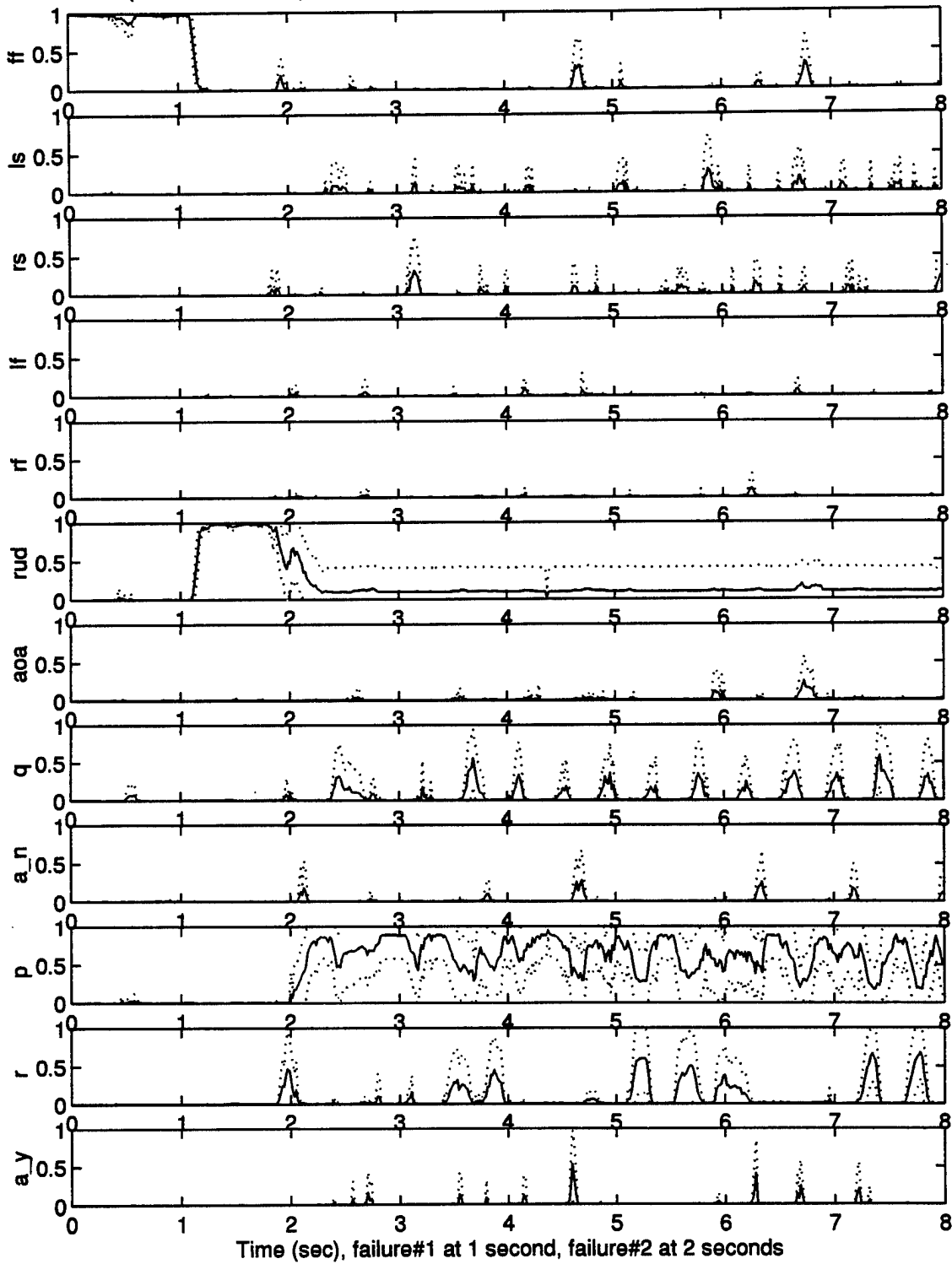
Mean (+/- One Std Dev) Dual-fail Probabilities of fail005.007 with reconfiguration: 10 runs



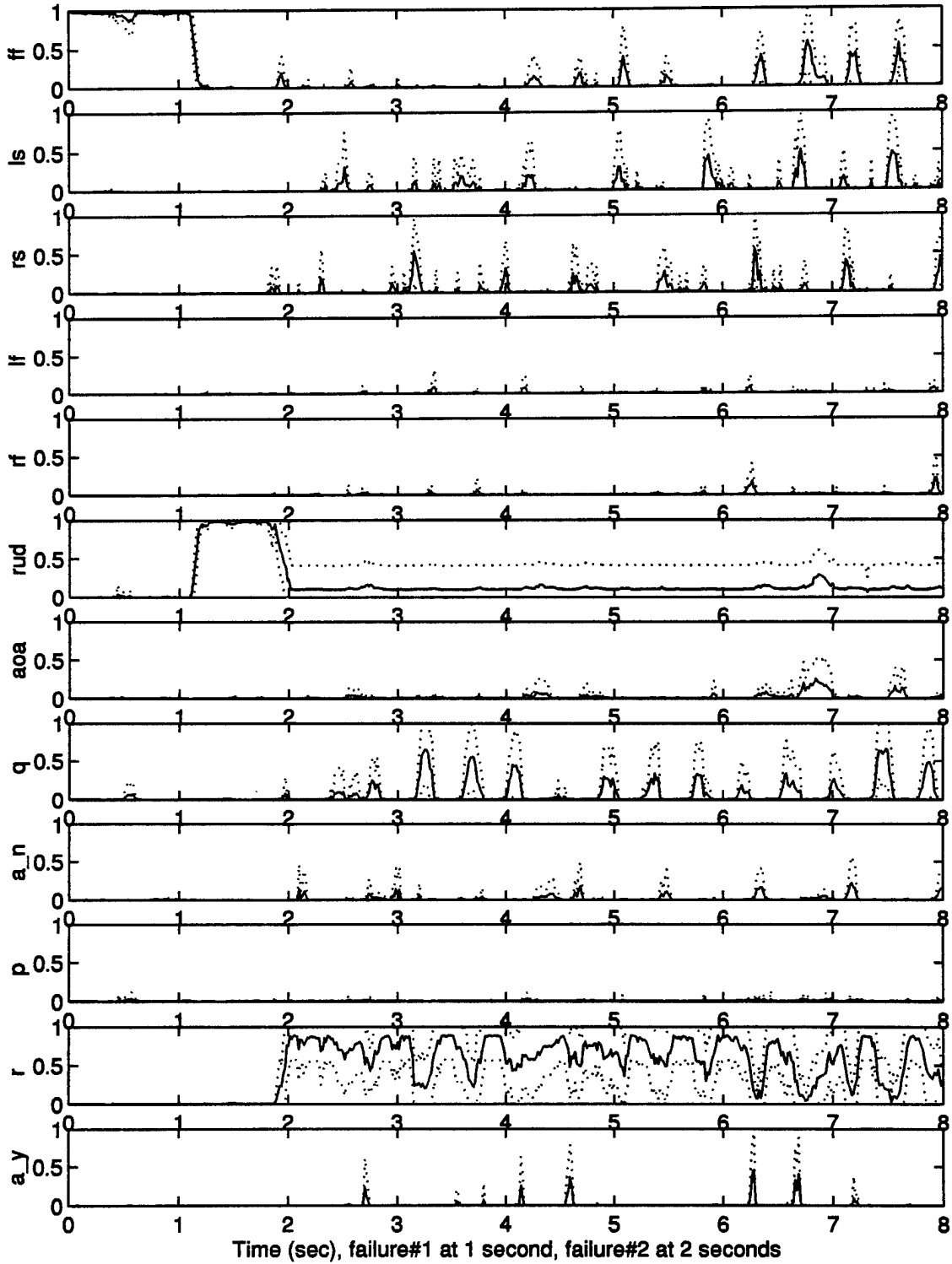
Mean (+/- One Std Dev) Dual-fail Probabilities of fail005.008 with reconfiguration: 10 runs



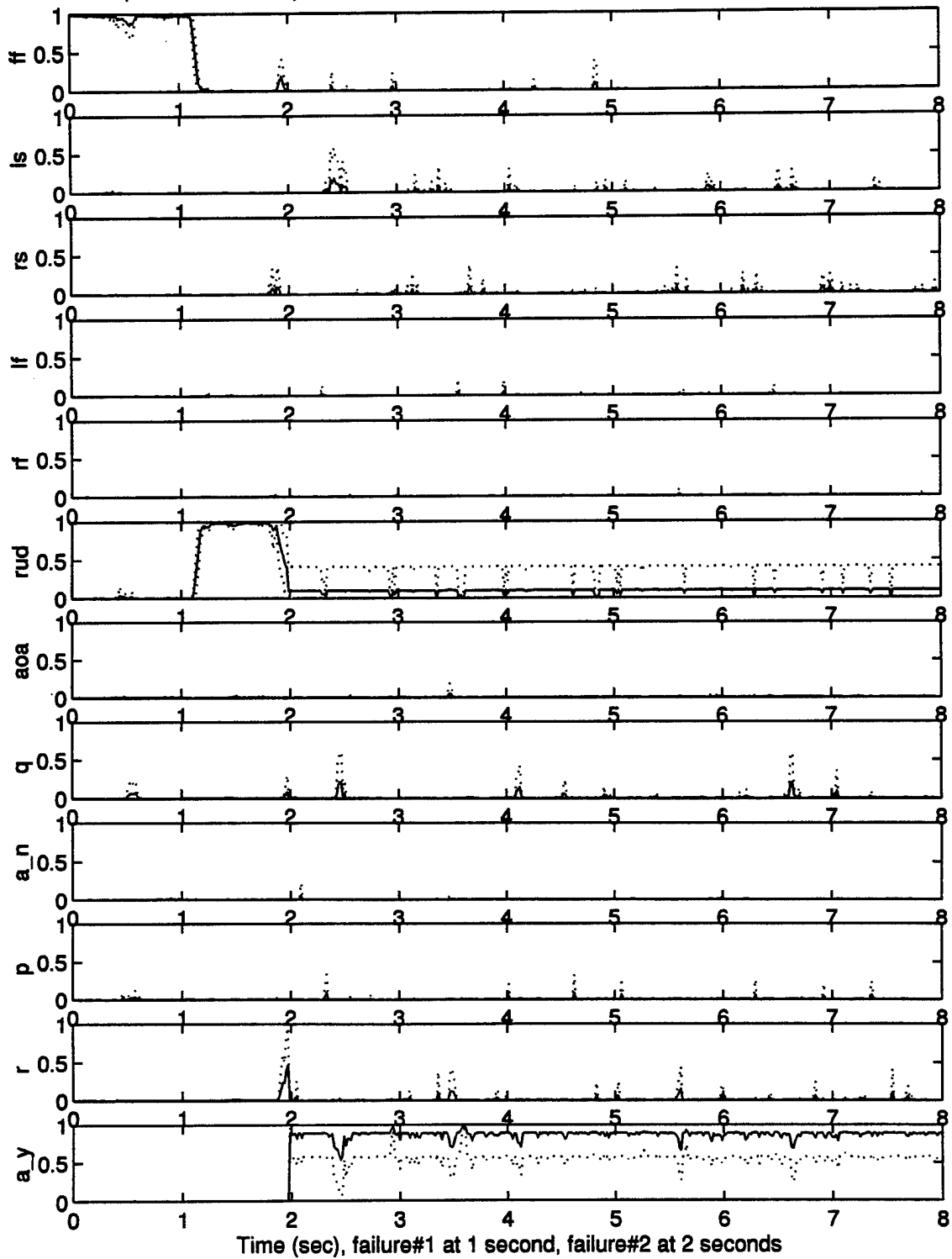
Mean (+/- One Std Dev) Dual-fail Probabilities of fail005.009 with reconfiguration: 10 runs



Mean (+/- One Std Dev) Dual-fail Probabilities of fail005.0010 with reconfiguration: 10 runs



Mean (+/- One Std Dev) Dual-fail Probabilities of fail005.0011 with reconfiguration: 10 runs



*Appendix D.2: Dual, 75% Actuator ($\epsilon = .25$) and 75%-Actuator / Total -Sensor Impairments,
Control Redistribution 'ON', Dither 'ON', No Maneuvers*

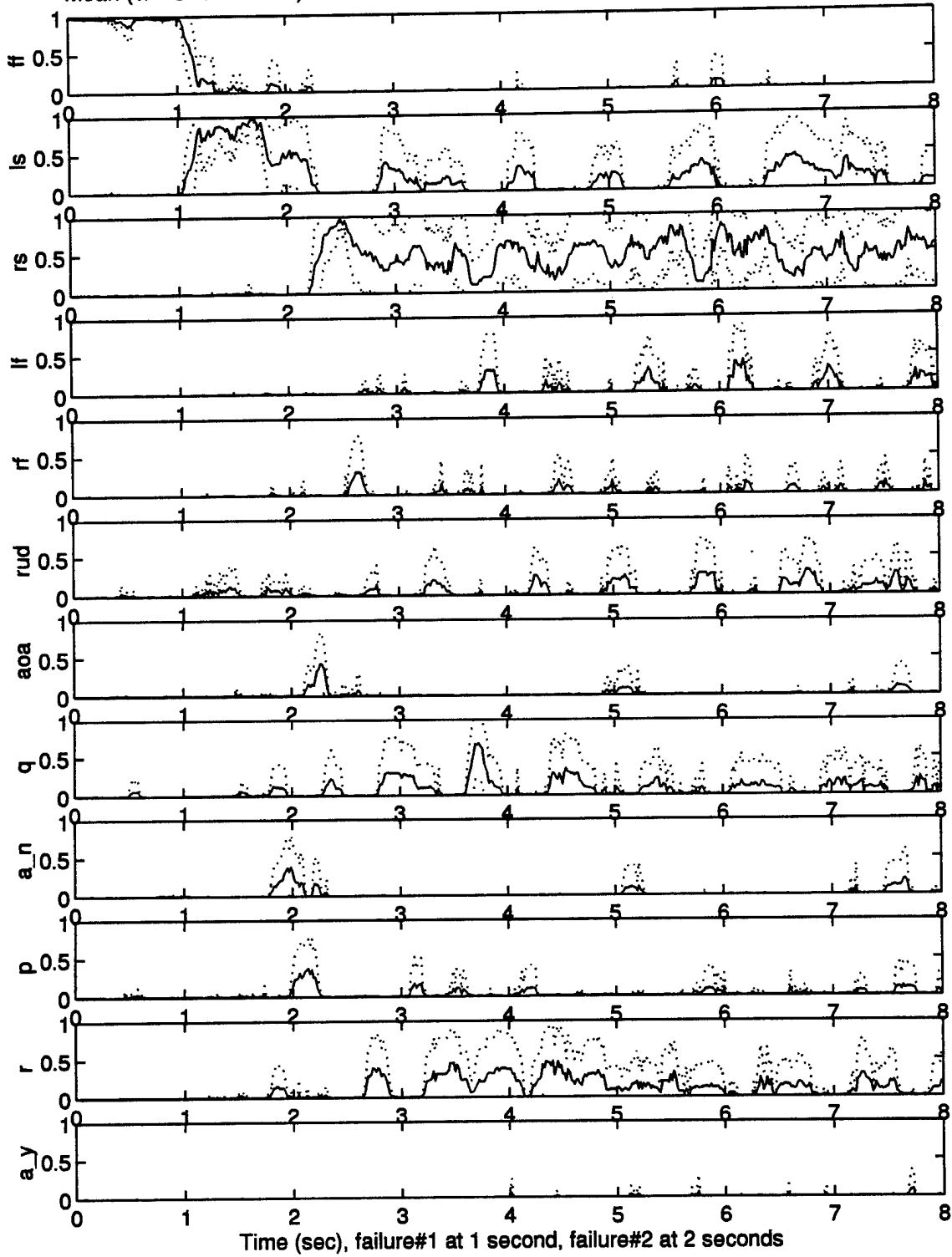
This appendix contains the individual probability plots for “75% actuator / 75% actuator” and “75% actuator / total sensor” dual impairment scenarios, *with* Control Reconfiguration (Redistribution) and with control dithering (Section 4.12.3). The first impairment is inserted at 1 second, followed by the second impairment at 2 seconds, and in all cases, there is no aircraft maneuvering. Table D.2 on the following page lists the impairment cases, by case number, which are to be found in this appendix. The leftmost column of Table D.2 represents the first impairment occurring at 1 second, while the top row represents the second impairment occurring at 2 seconds. The table entries list the failure codes found in the plot titles for the failure case represented by the table row and column. **Bold** entries correspond to cases of no second impairment. As an example, the entry for a 75% left stabilator (LS) impairment at 1 second, followed by a 75% right flaperon (RF) impairment at 2 seconds is found in entry ‘(LS, RF)’ in the table, and the corresponding failure case is ‘fail251.254’. The convention was to use effectiveness, ϵ , in naming the plots, and hence ‘fail251.254’ corresponds to 25% actuator *effectiveness*, or a 75% actuator impairment. The probability plot will contain this code (‘fail251.254’) in the plot title. In fact, for this specific case, the plot title is: “Mean (+ / - One Std Dev) Dual-fail Probabilities of fail251.254 with reconfiguration: 10 runs”. The reader is reminded that, after the switch to the Level ‘1’ filter bank, the meanings of the probability traces in the plots (except for the fully functional trace, which retains the same meaning) change to that of the first impairment *plus* the second impairment.

Second Impairment

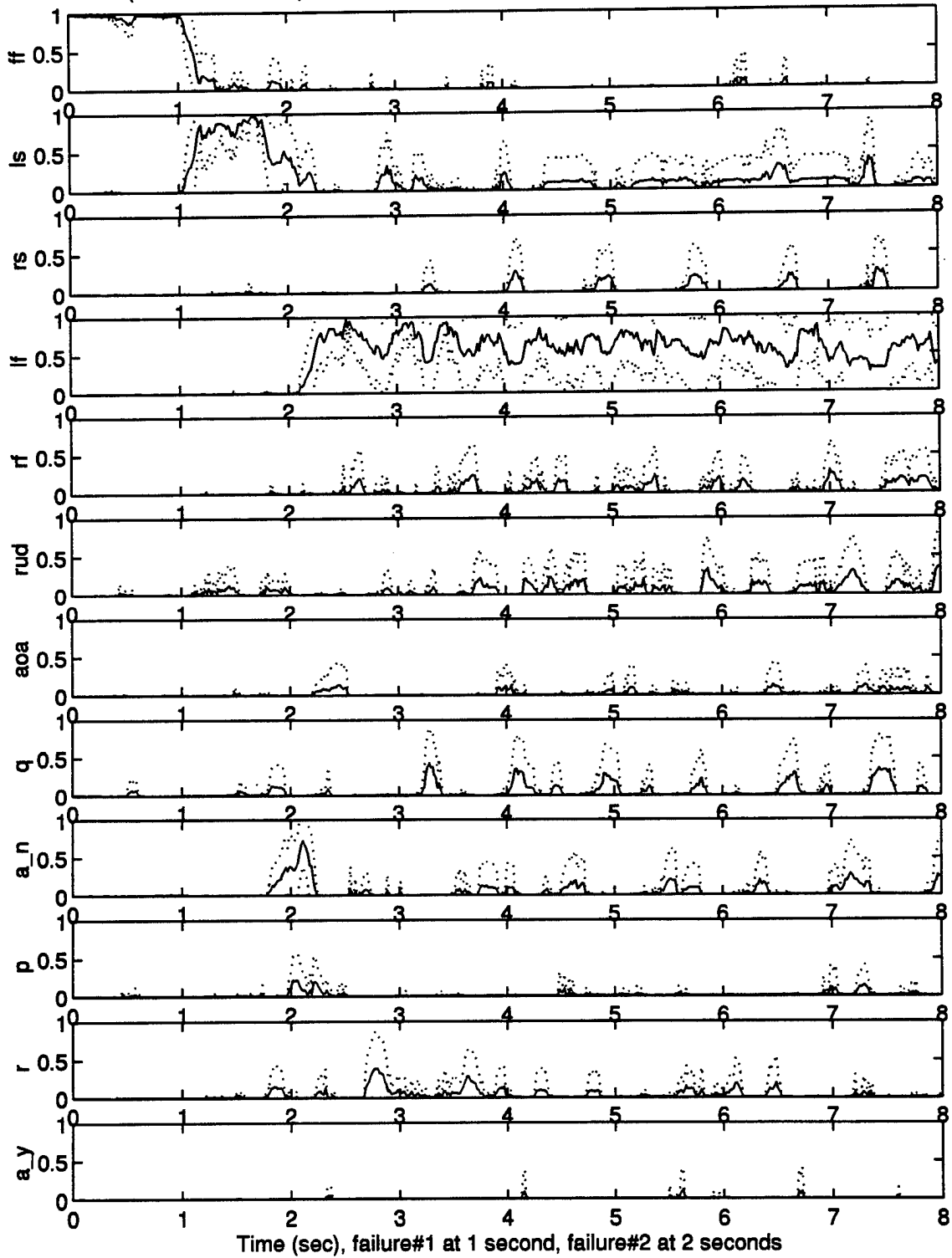
	LS (75%)	RS (75%)	LF (75%)	RF (75%)	RUD (75%)	AOA (100%)	Q (100%)	A_n (100%)	P (100%)	R (100%)	A_y (100%)
LS (75%)	fail251.250	fail251.252	fail251.253	fail251.254	fail251.255	fail251.06	fail251.07	fail251.08	fail251.09	fail251.010	fail251.011
RS (75%)	fail252.251	fail252.250	fail252.253	fail252.254	fail252.255	fail252.06	fail252.07	fail252.08	fail252.09	fail252.010	fail252.011
LF (75%)	fail253.251	fail253.252	fail253.250	fail253.254	fail253.255	fail253.06	fail253.07	fail253.08	fail253.09	fail253.010	fail253.011
RF (75%)	fail254.251	fail254.252	fail254.253	fail254.250	fail254.255	fail254.06	fail254.07	fail254.08	fail254.09	fail254.010	fail254.011
RUD (75%)	fail255.251	fail255.252	fail255.253	fail255.254	fail255.250	fail255.06	fail255.07	fail255.08	fail255.09	fail255.010	fail255.011

Table D.2 A Listing of All Probability Plots Found in Appendix D.2 by Failure Case

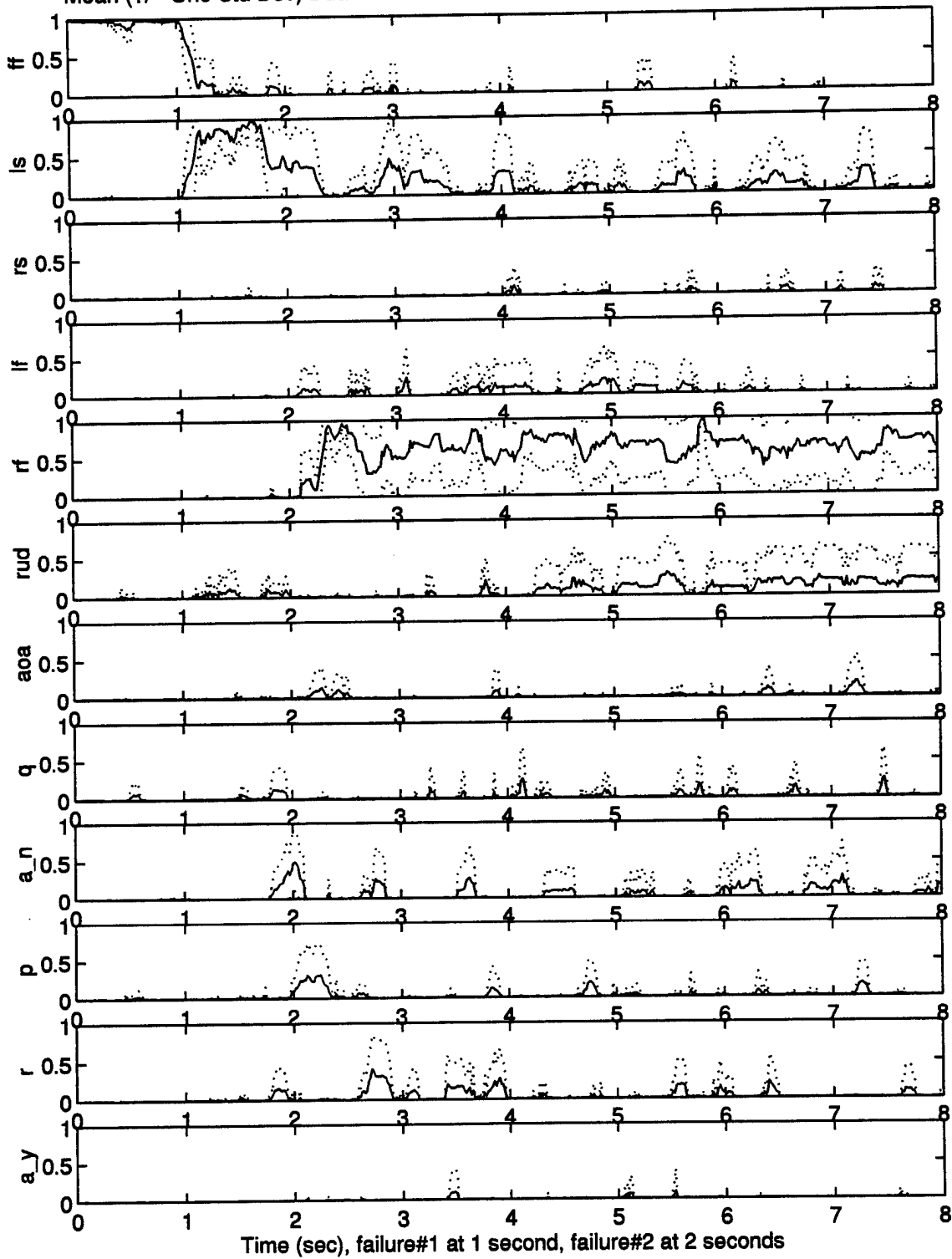
Mean (+/- One Std Dev) Dual-fail Probabilities of fail251.252 with reconfiguration: 10 runs



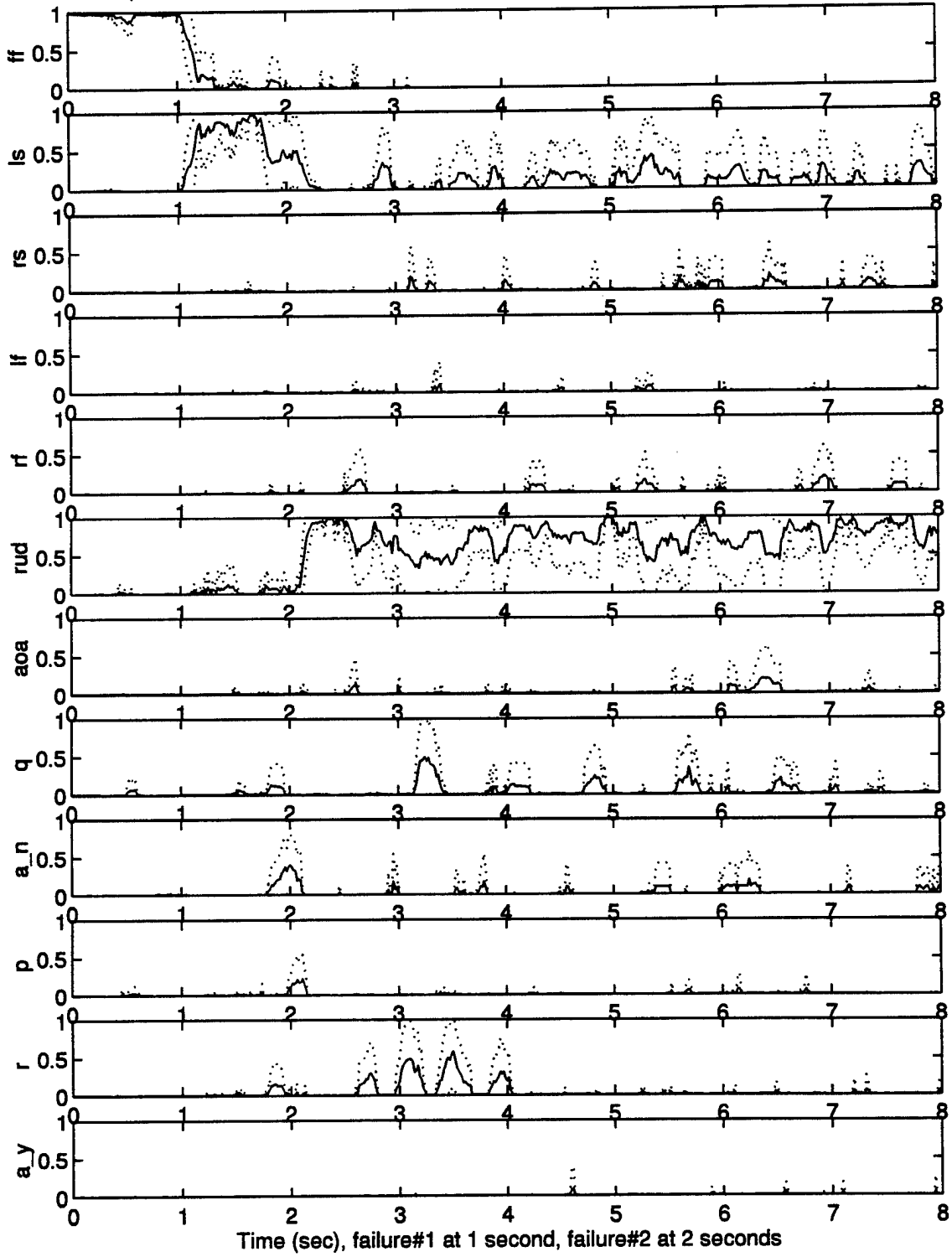
Mean (+/- One Std Dev) Dual-fail Probabilities of fail251.253 with reconfiguration: 10 runs



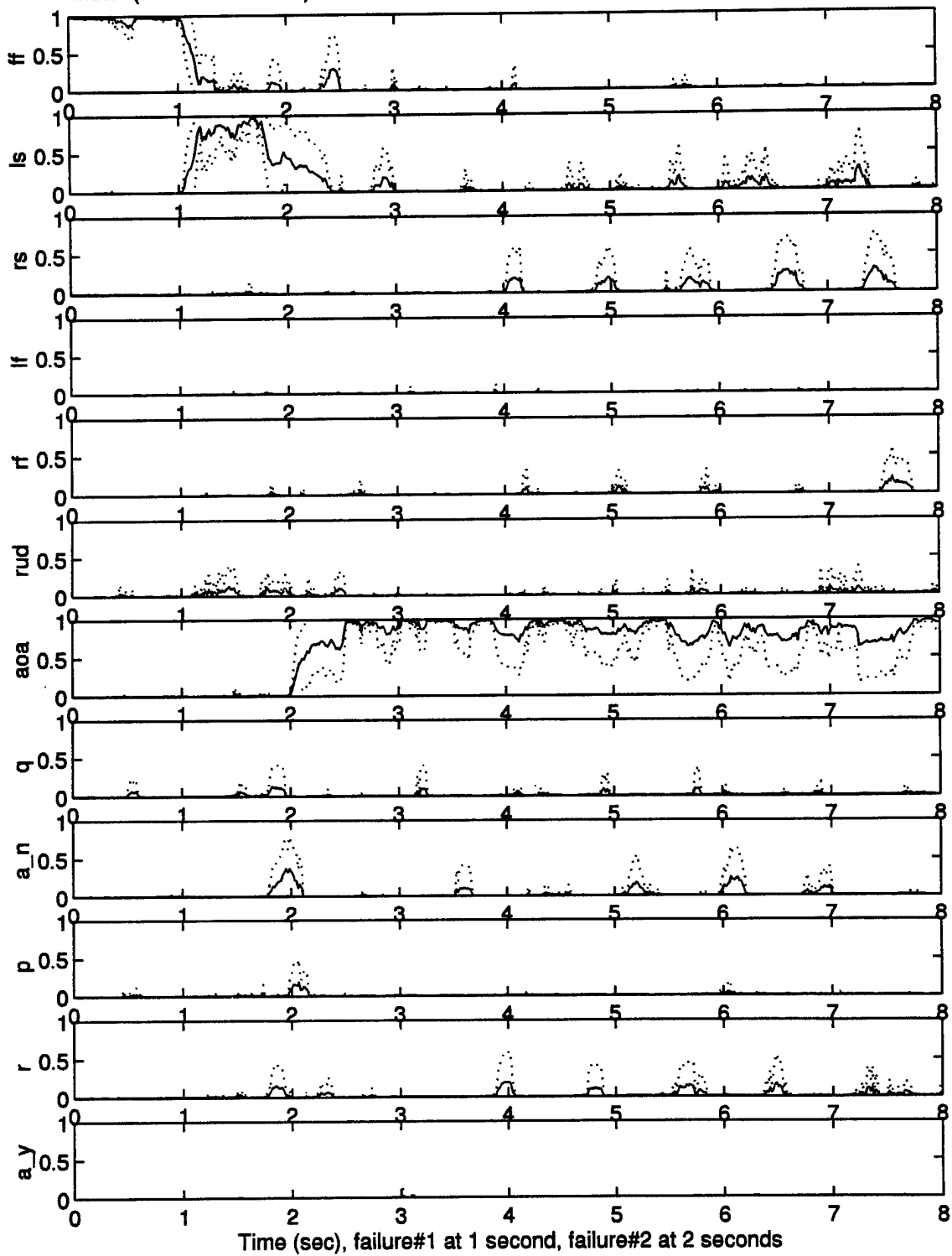
Mean (+/- One Std Dev) Dual-fail Probabilities of fail251.254 with reconfiguration: 10 runs



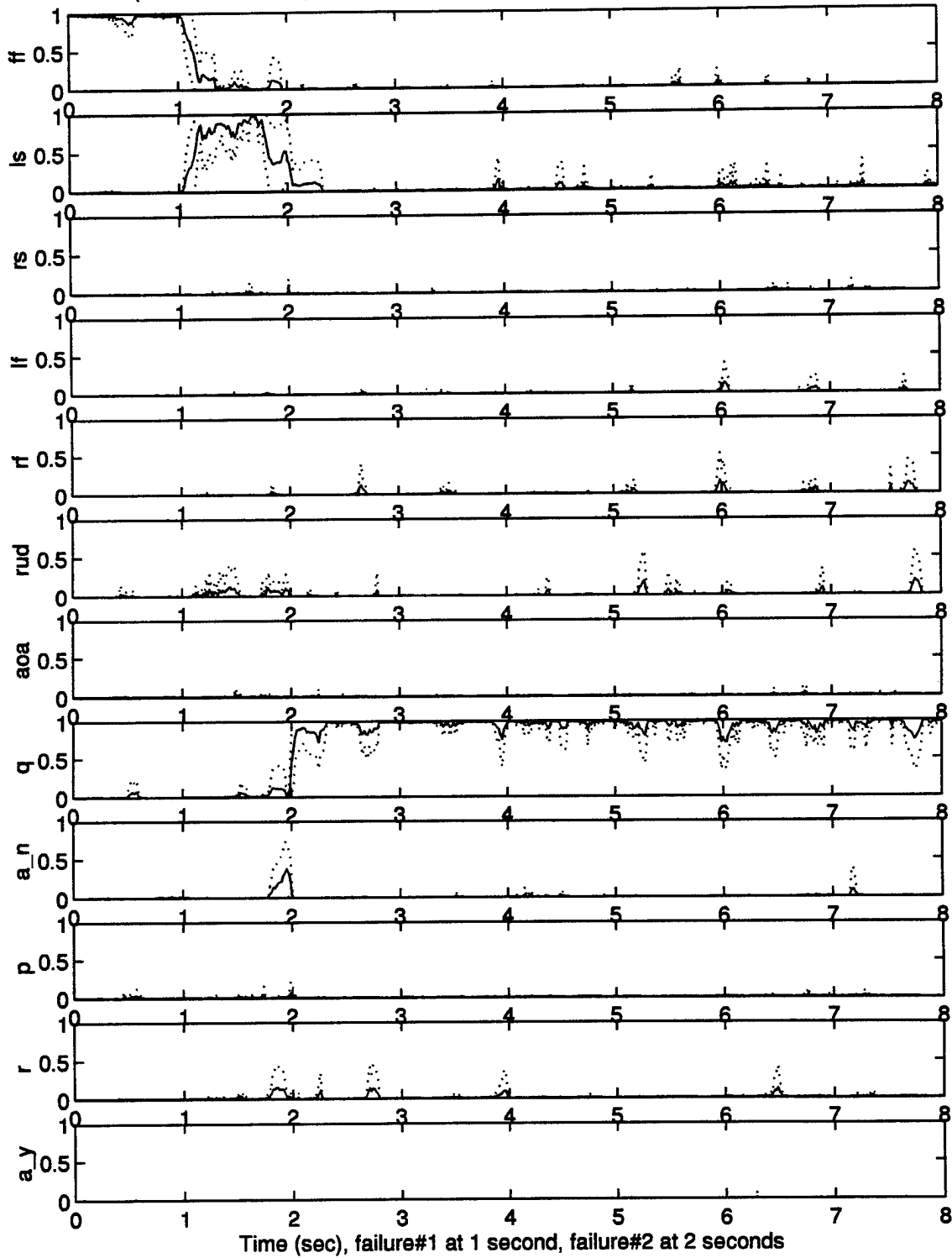
Mean (+/- One Std Dev) Dual-fail Probabilities of fail251.255 with reconfiguration: 10 runs



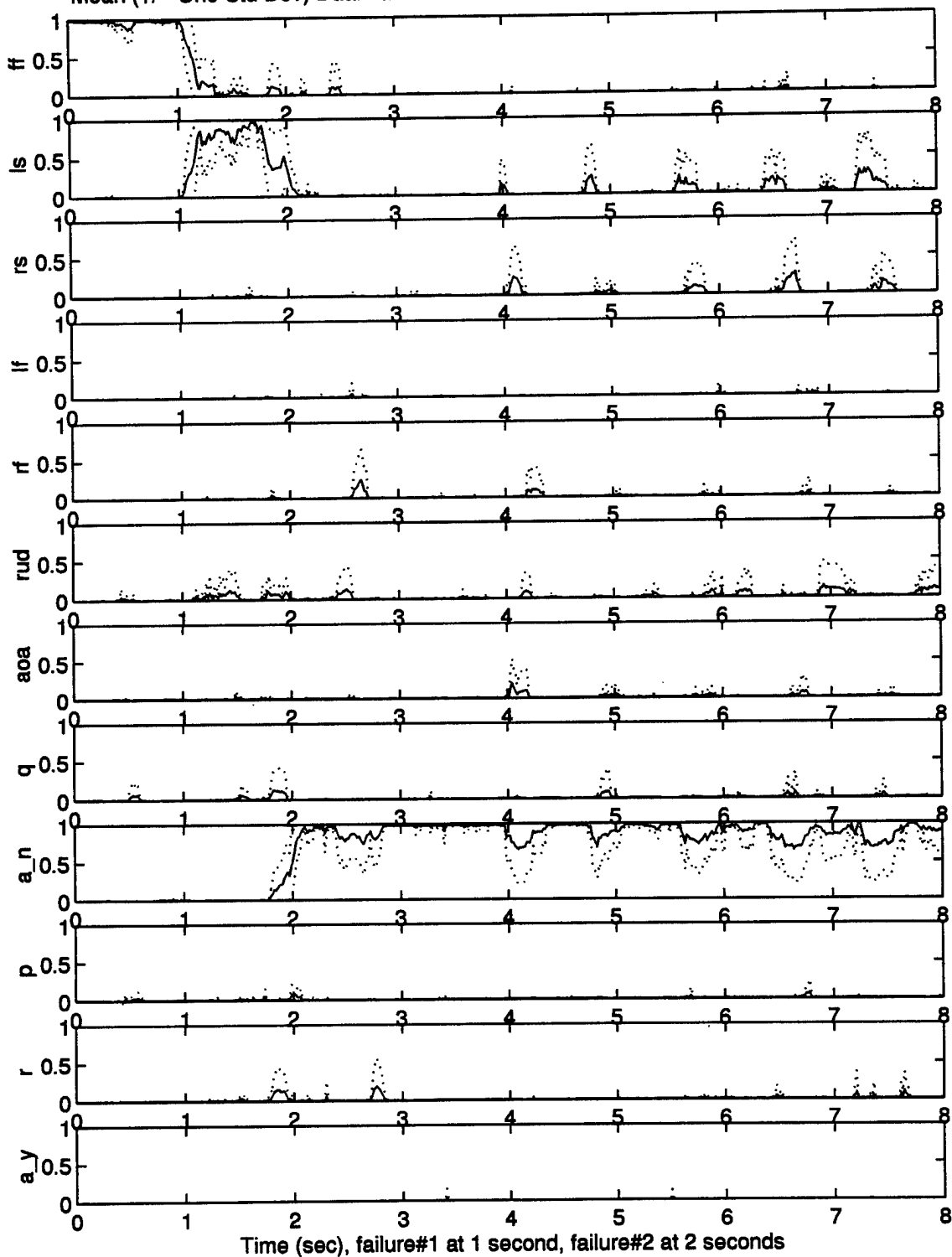
Mean (+/- One Std Dev) Dual-fail Probabilities of fail251.06 with reconfiguration: 10 runs



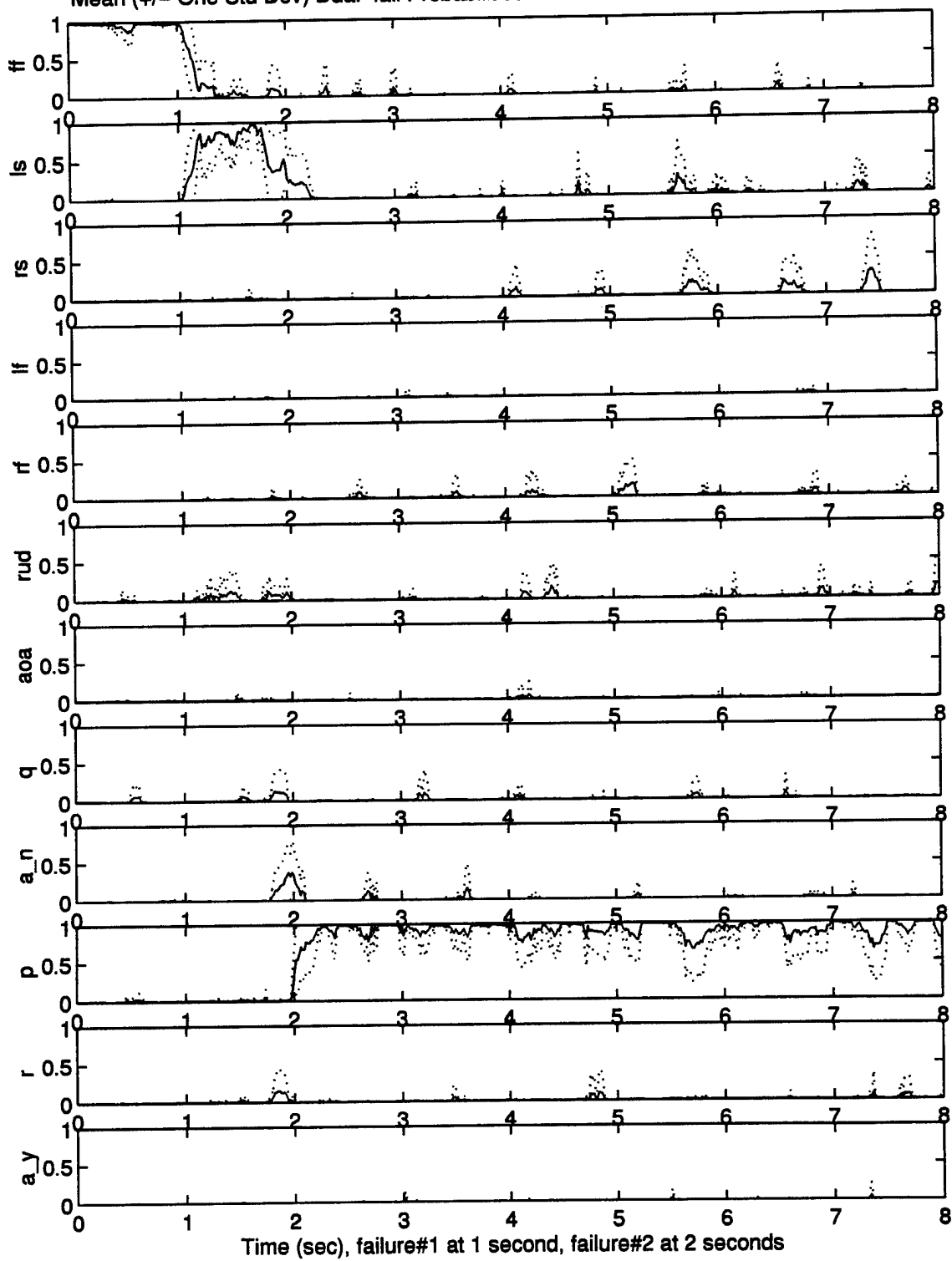
Mean (+/- One Std Dev) Dual-fail Probabilities of fail251.07 with reconfiguration: 10 runs



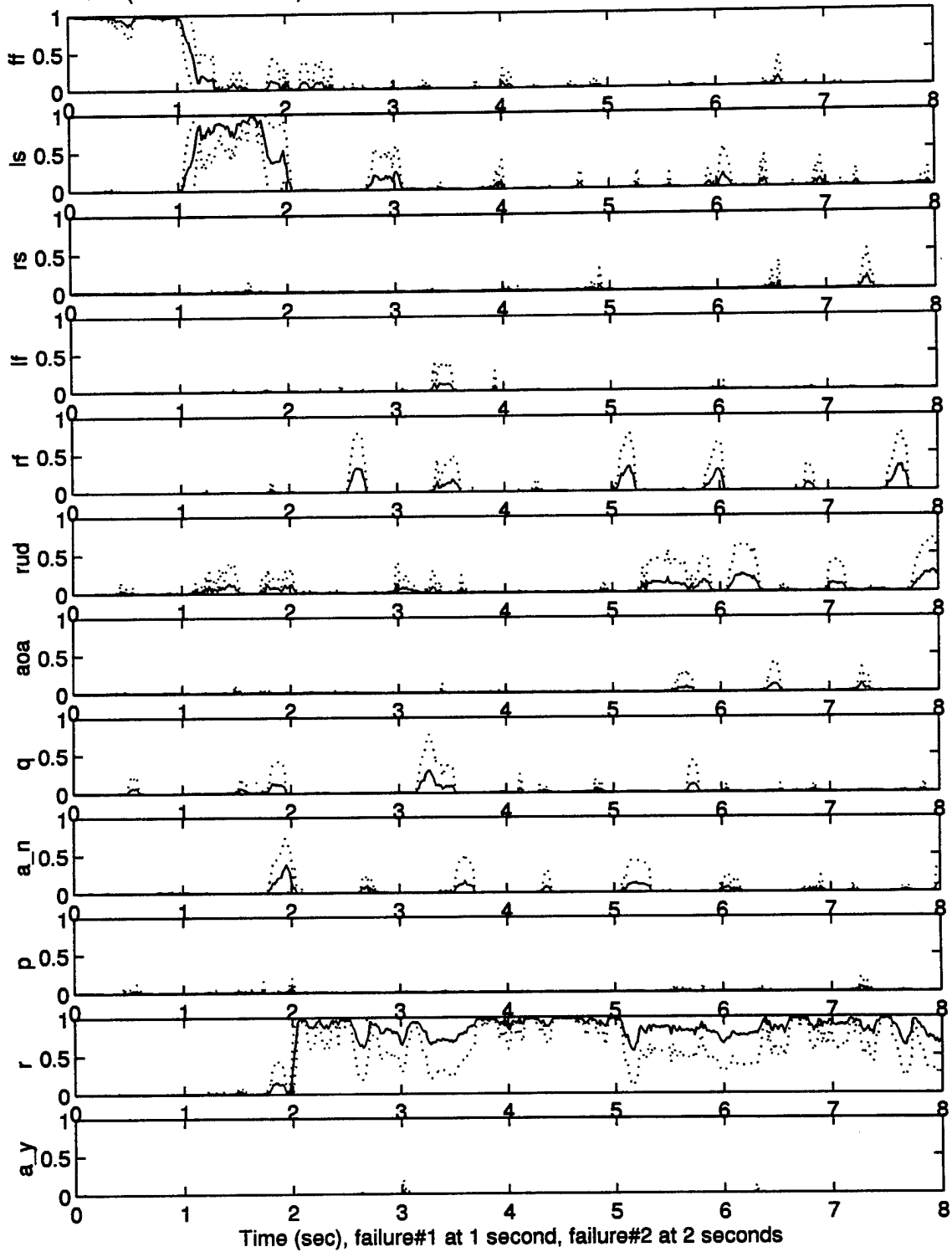
Mean (+/- One Std Dev) Dual-fail Probabilities of fail251.08 with reconfiguration: 10 runs



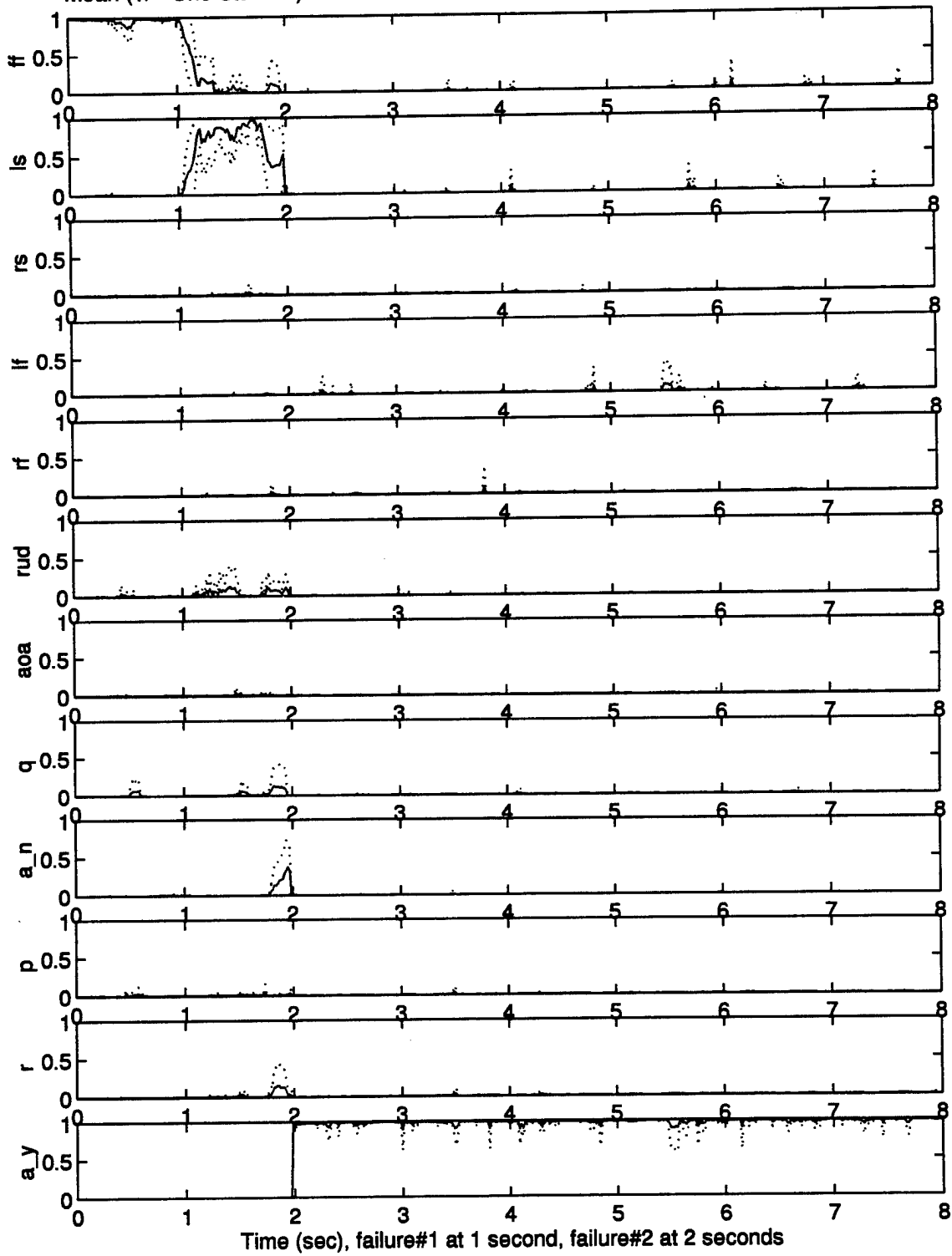
Mean (+/- One Std Dev) Dual-fail Probabilities of fail251.09 with reconfiguration: 10 runs



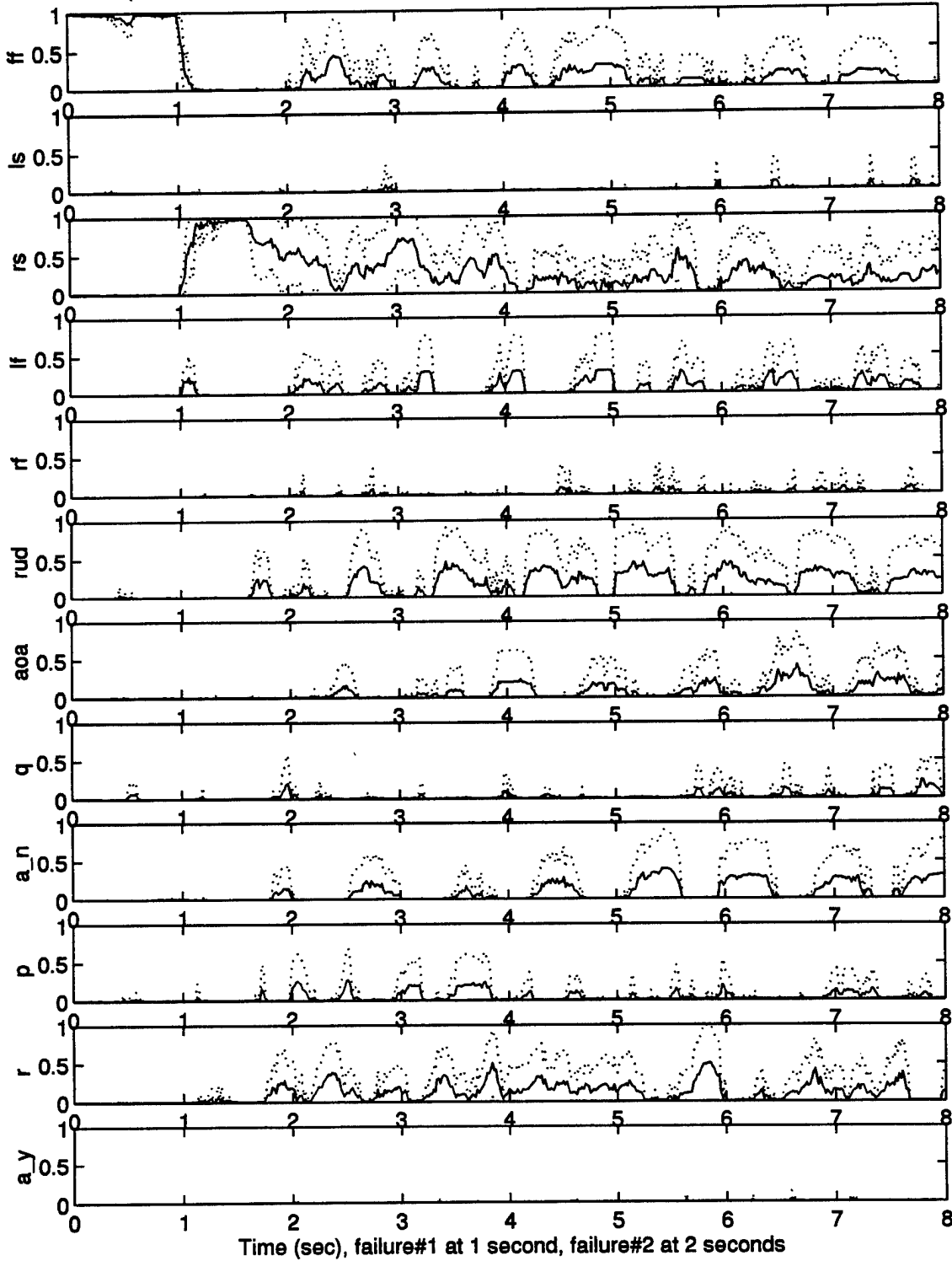
Mean (+/- One Std Dev) Dual-fail Probabilities of fail251.010 with reconfiguration: 10 runs



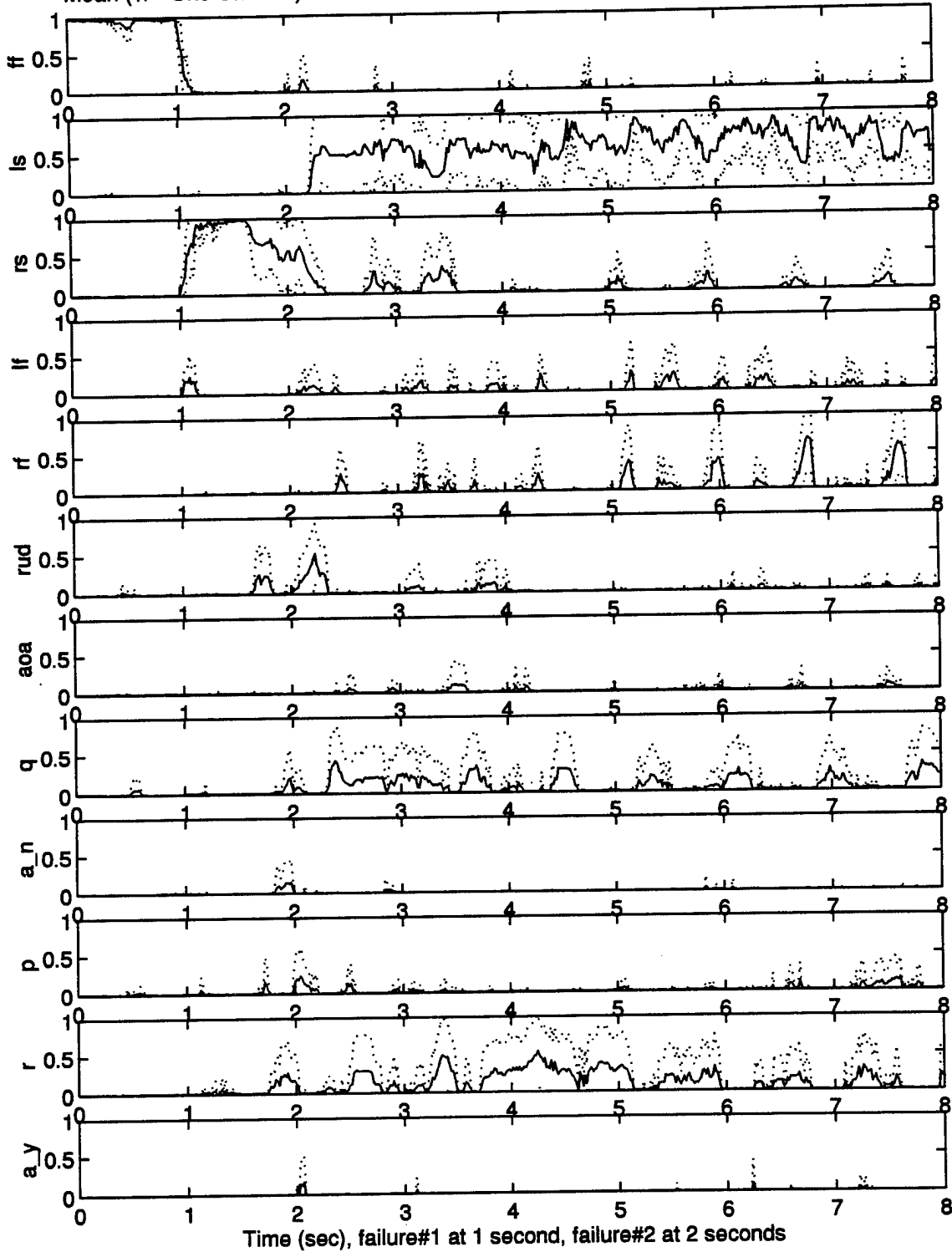
Mean (+/- One Std Dev) Dual-fail Probabilities of fail251.011 with reconfiguration: 10 runs



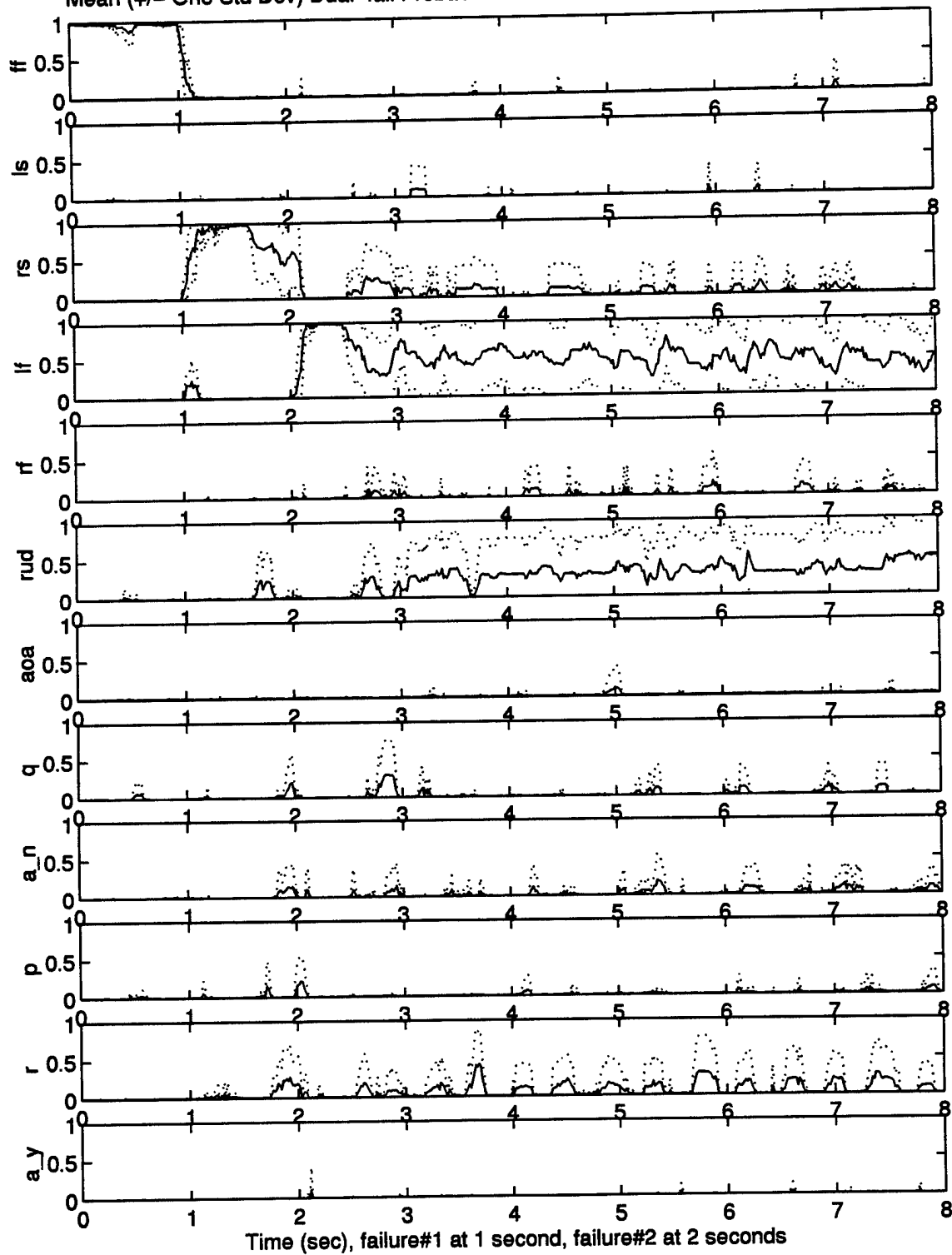
Mean (+/- One Std Dev) Dual-fail Probabilities of fail252.250 with reconfiguration: 10 runs



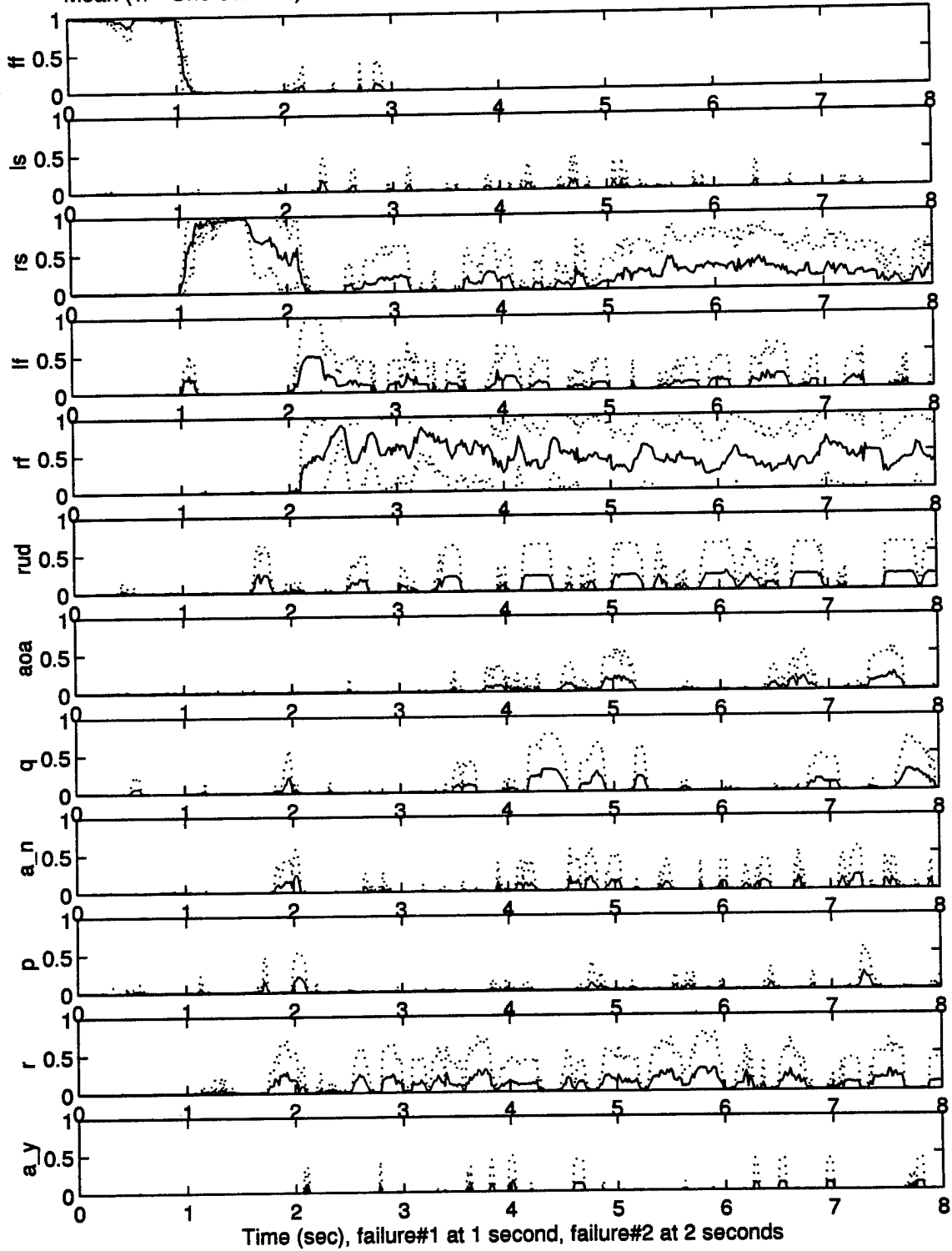
Mean (+/- One Std Dev) Dual-fail Probabilities of fail252.251 with reconfiguration: 10 runs



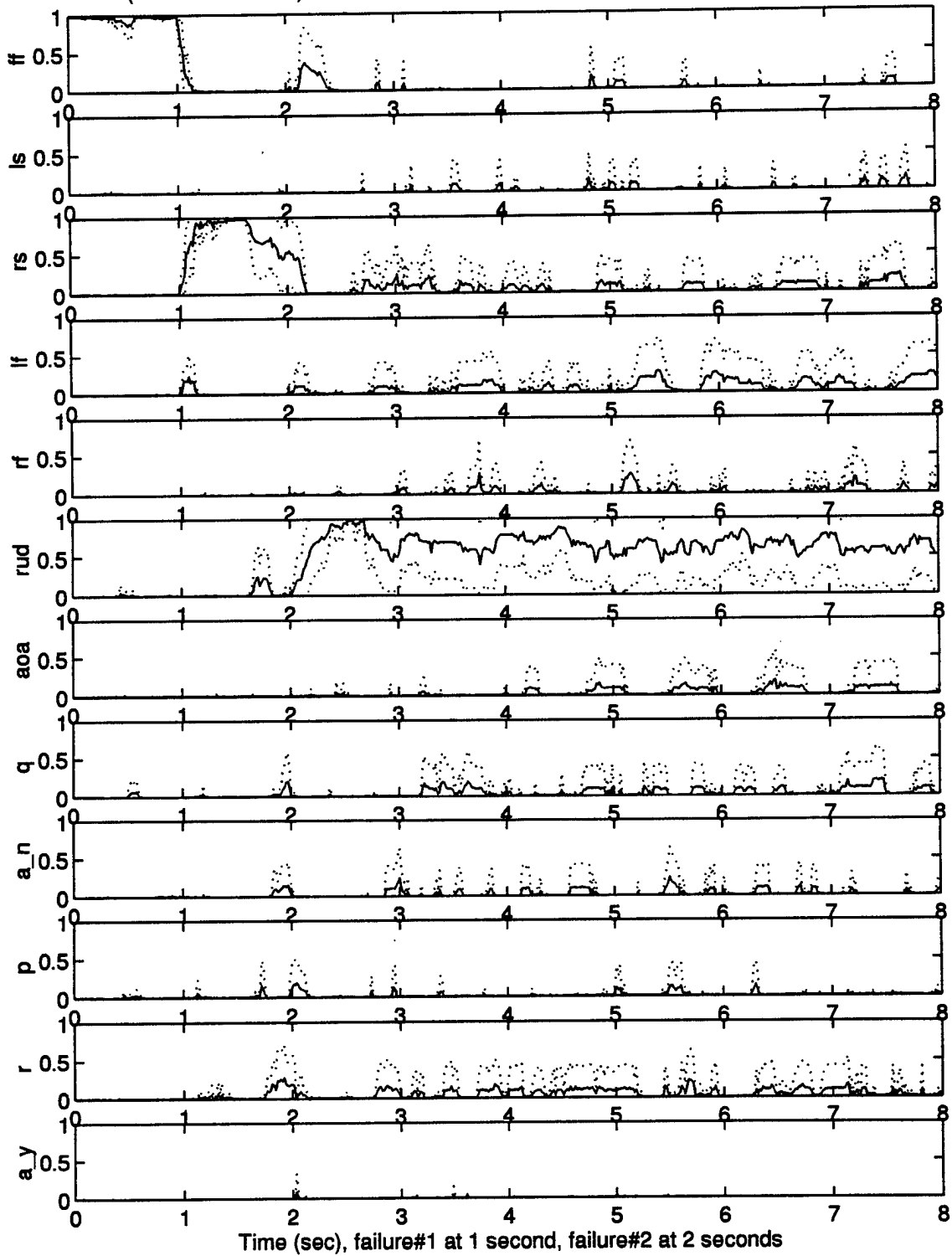
Mean (+/- One Std Dev) Dual-fail Probabilities of fail252.253 with reconfiguration: 10 runs



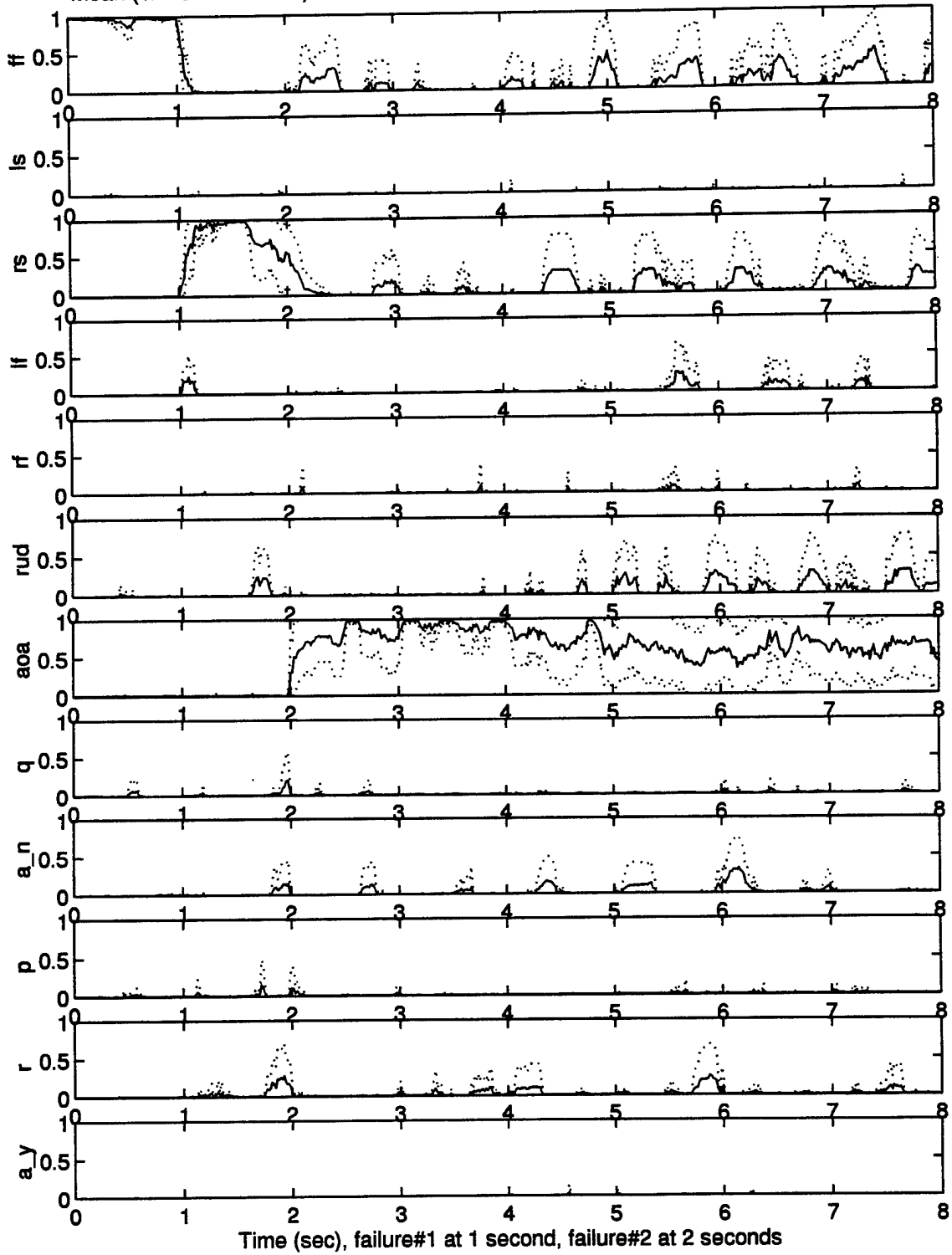
Mean (+/- One Std Dev) Dual-fail Probabilities of fail252.254 with reconfiguration: 10 runs



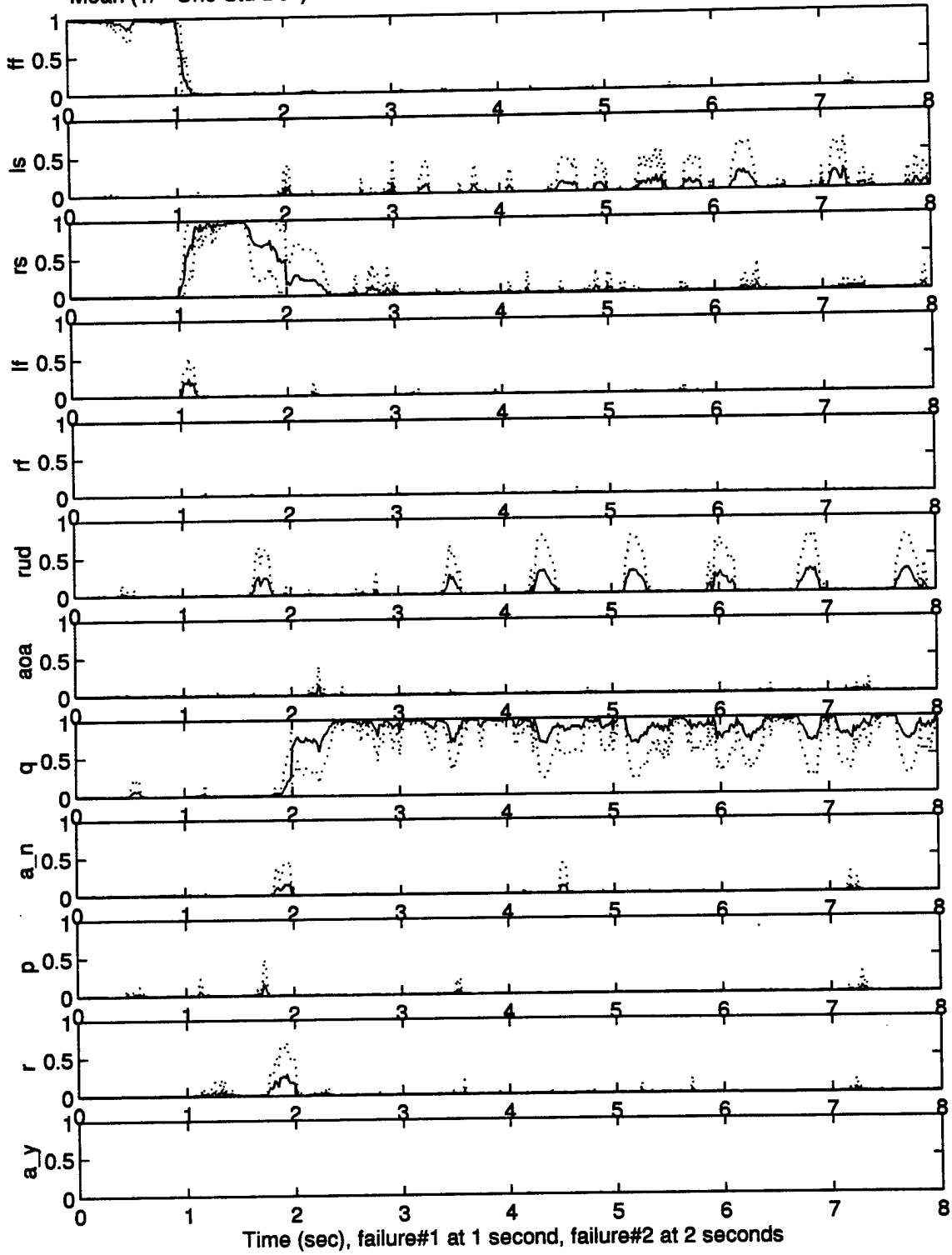
Mean (+/- One Std Dev) Dual-fail Probabilities of fail252.255 with reconfiguration: 10 runs



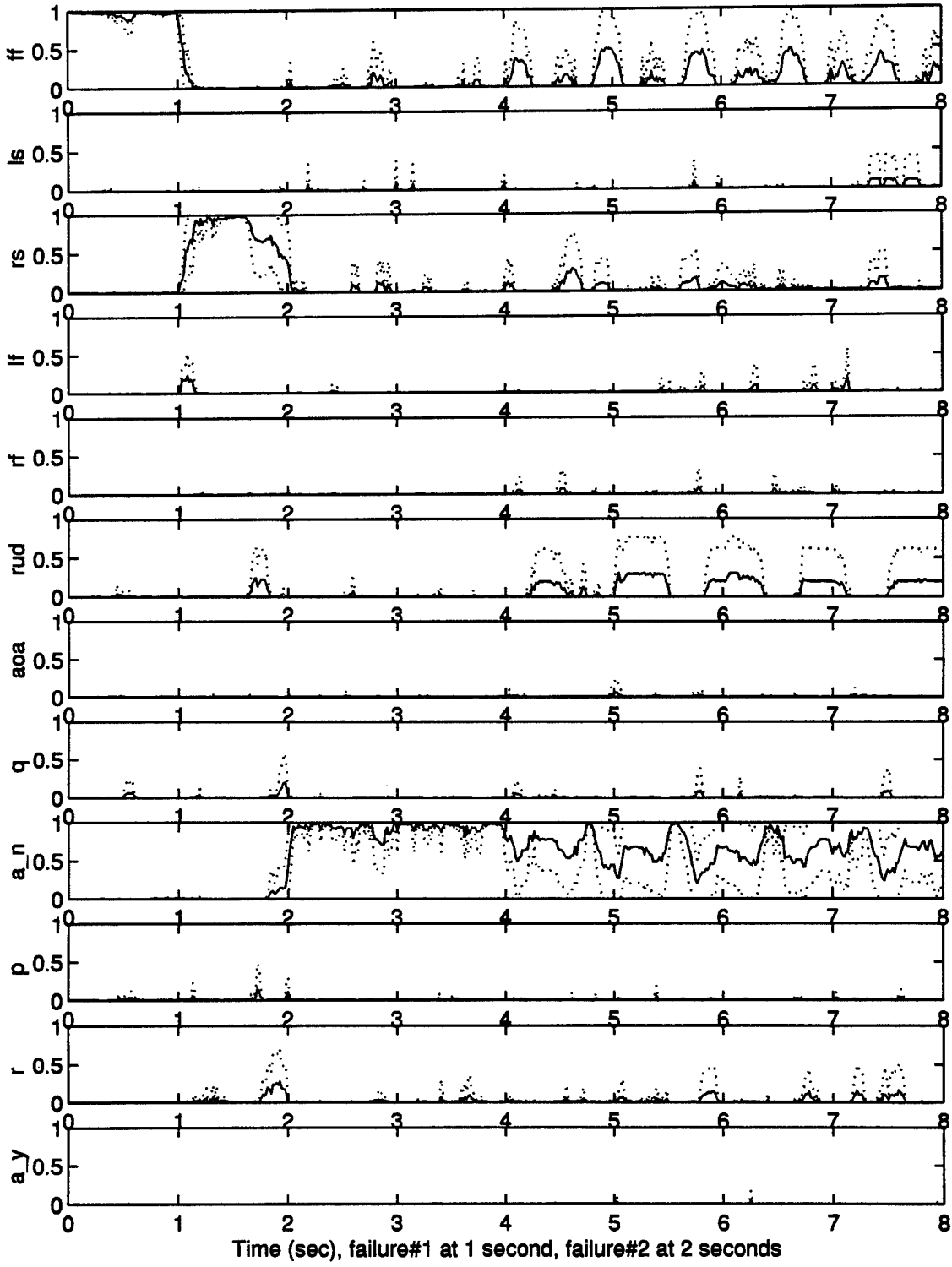
Mean (+/- One Std Dev) Dual-fail Probabilities of fail252.06 with reconfiguration: 10 runs



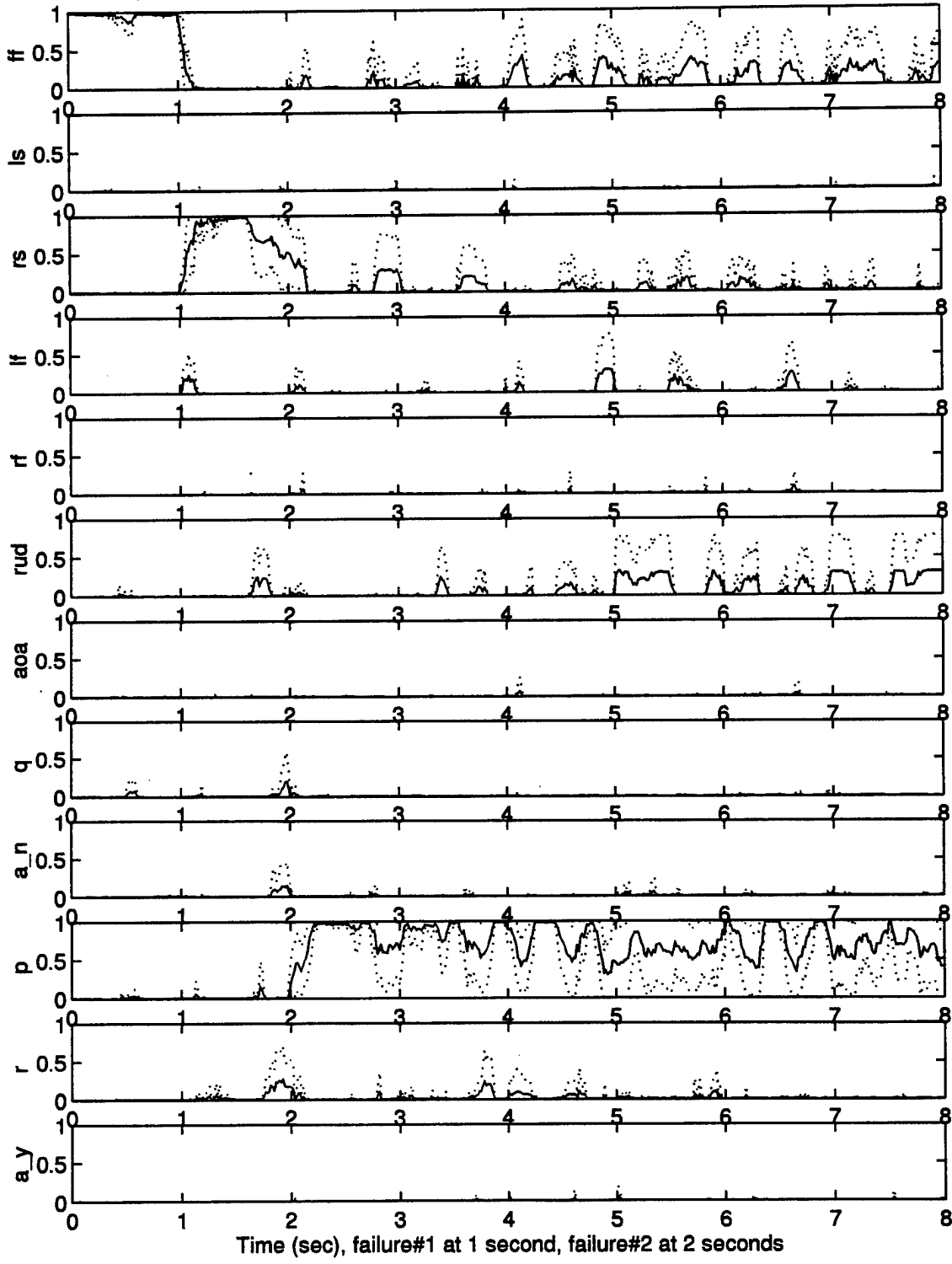
Mean (+/- One Std Dev) Dual-fail Probabilities of fail252.07 with reconfiguration: 10 runs



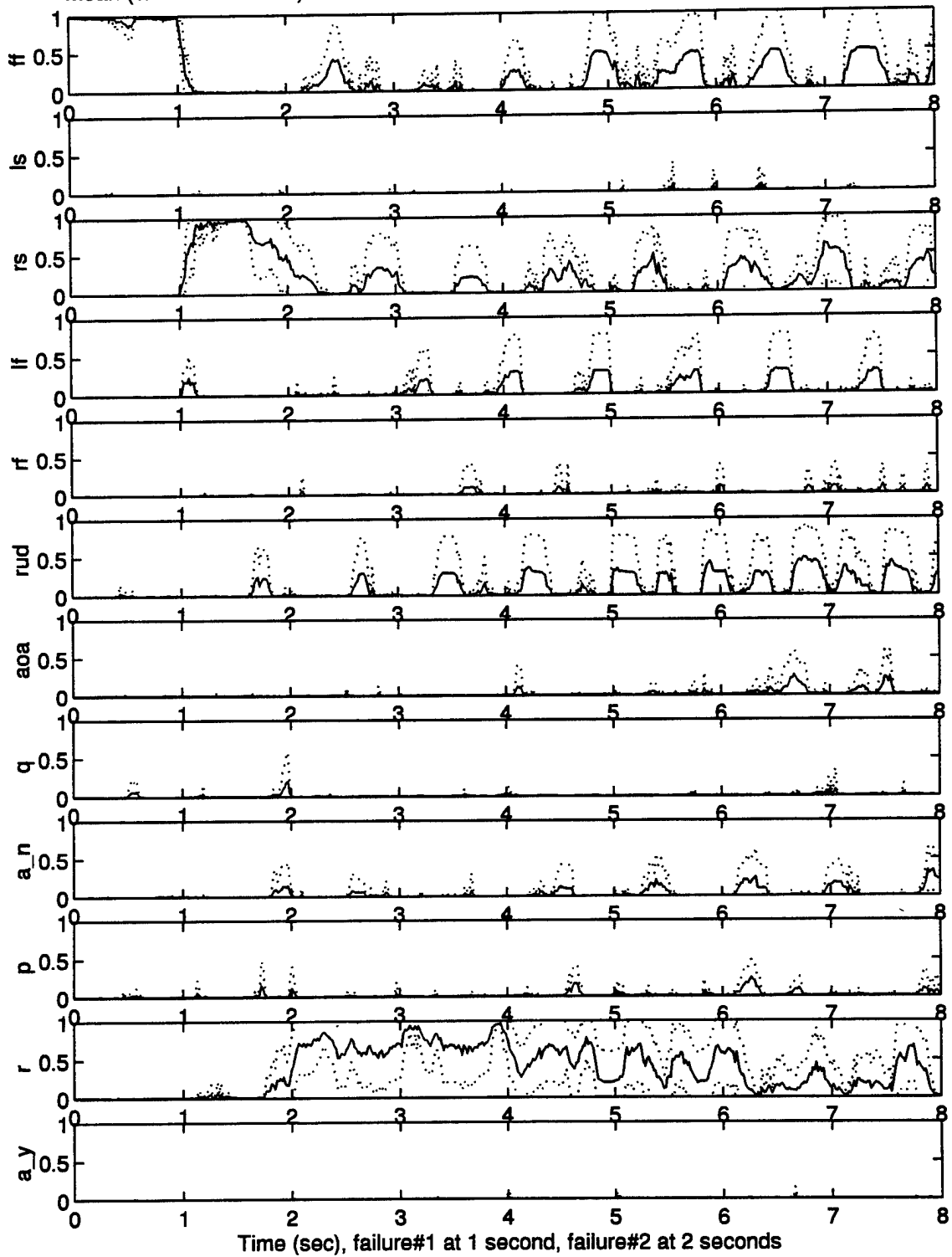
Mean (+/- One Std Dev) Dual-fail Probabilities of fail252.08 with reconfiguration: 10 runs



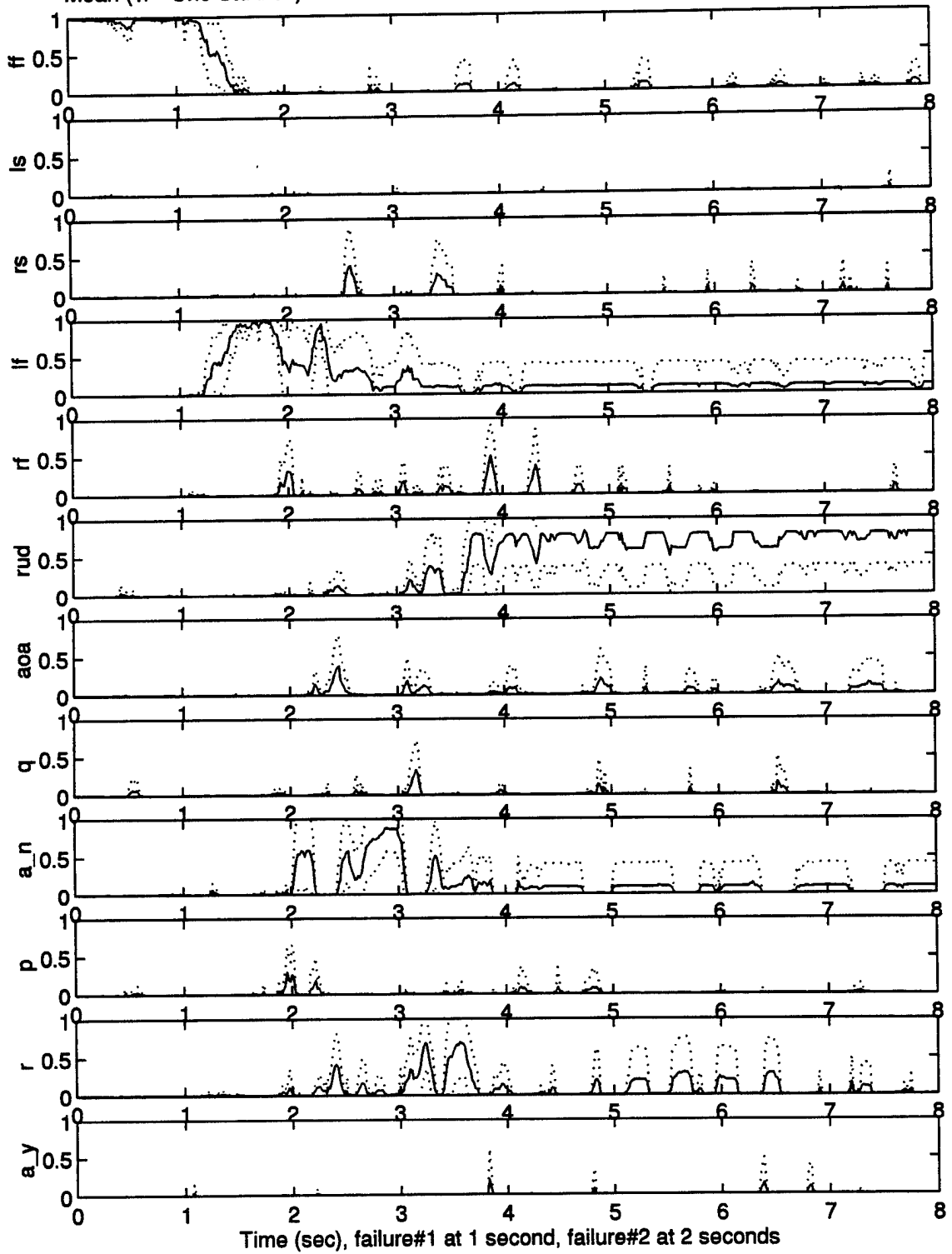
Mean (+/- One Std Dev) Dual-fail Probabilities of fail252.09 with reconfiguration: 10 runs



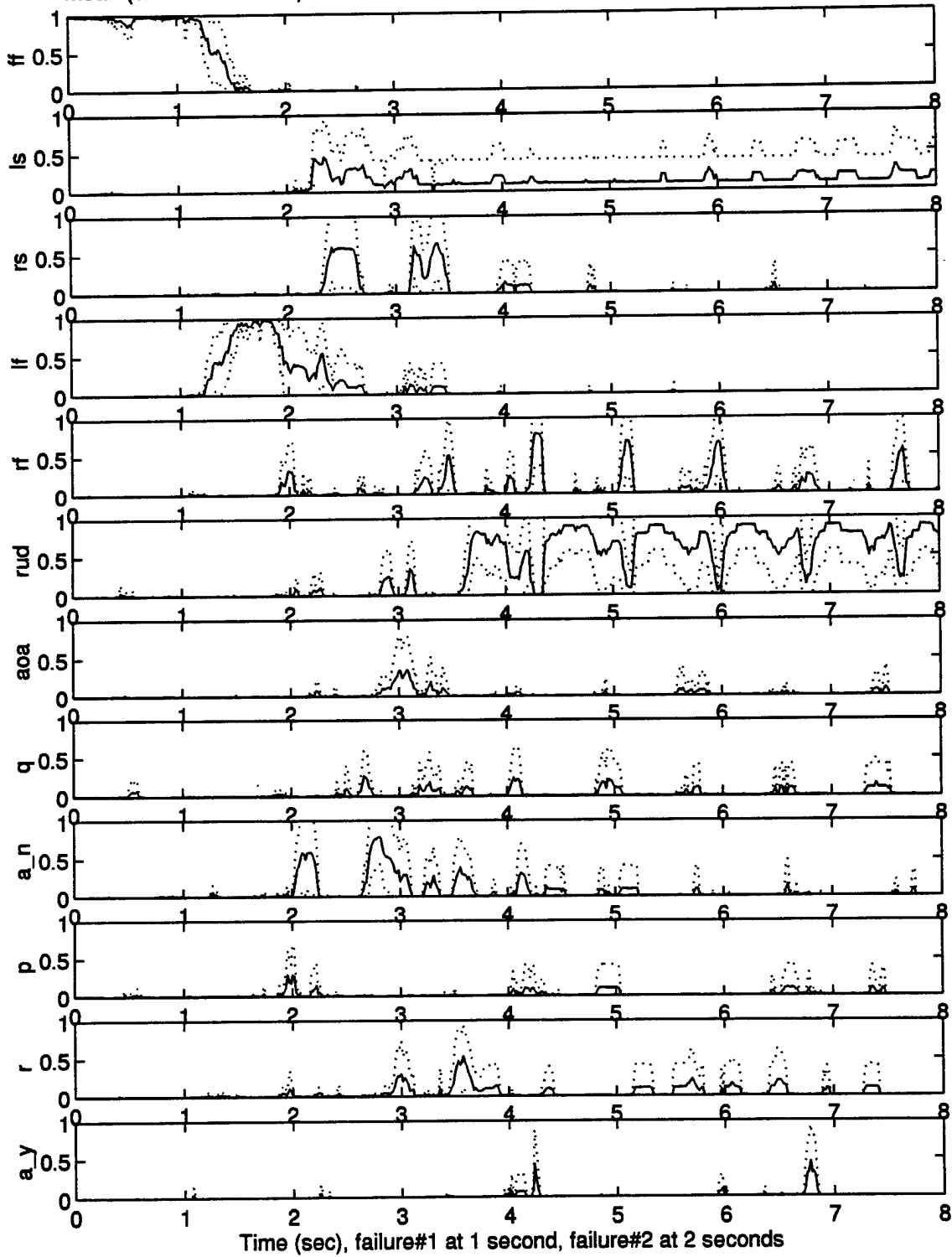
Mean (+/- One Std Dev) Dual-fail Probabilities of fail252.010 with reconfiguration: 10 runs



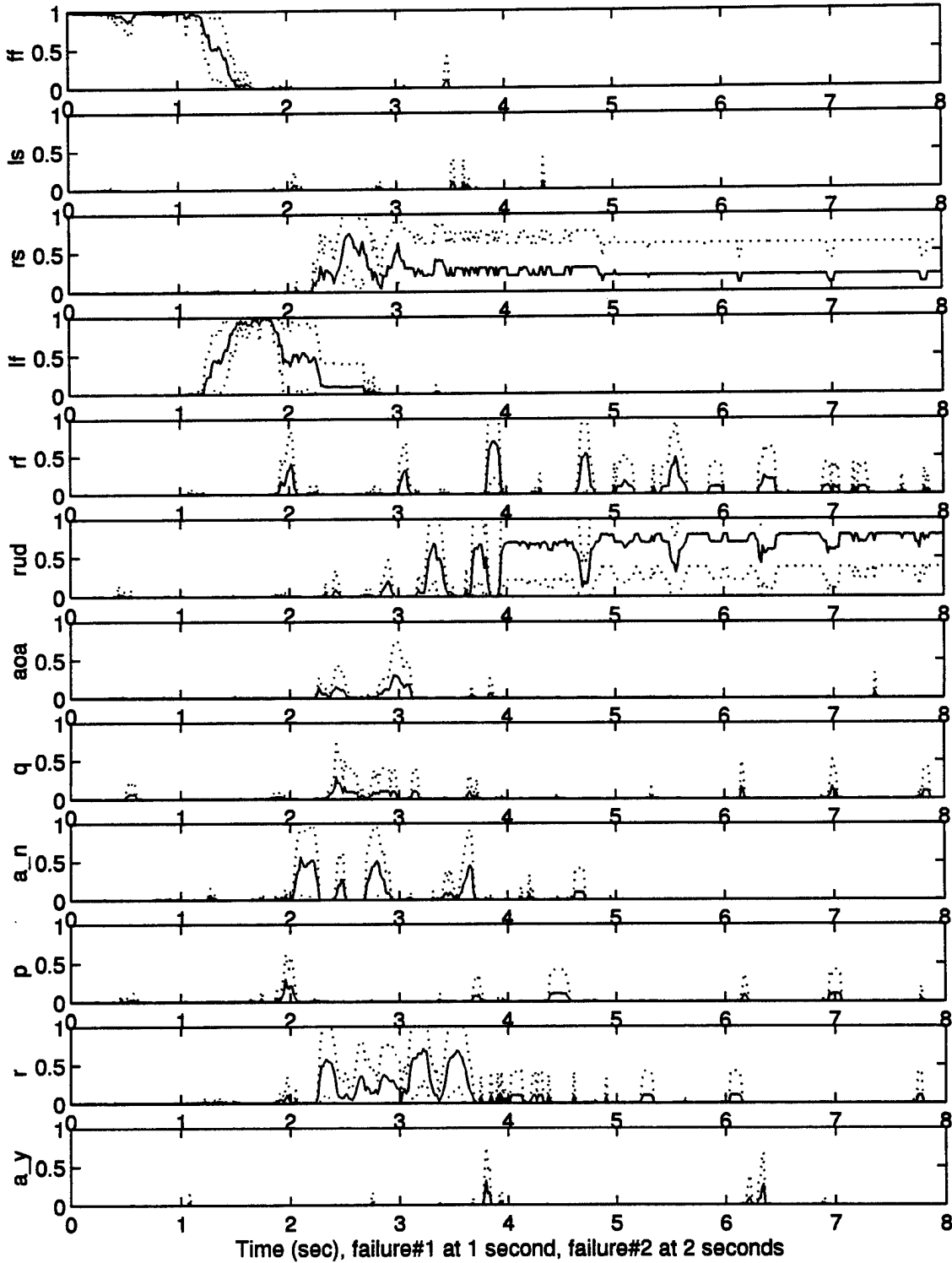
Mean (+/- One Std Dev) Dual-fail Probabilities of fail253.250 with reconfiguration: 10 runs



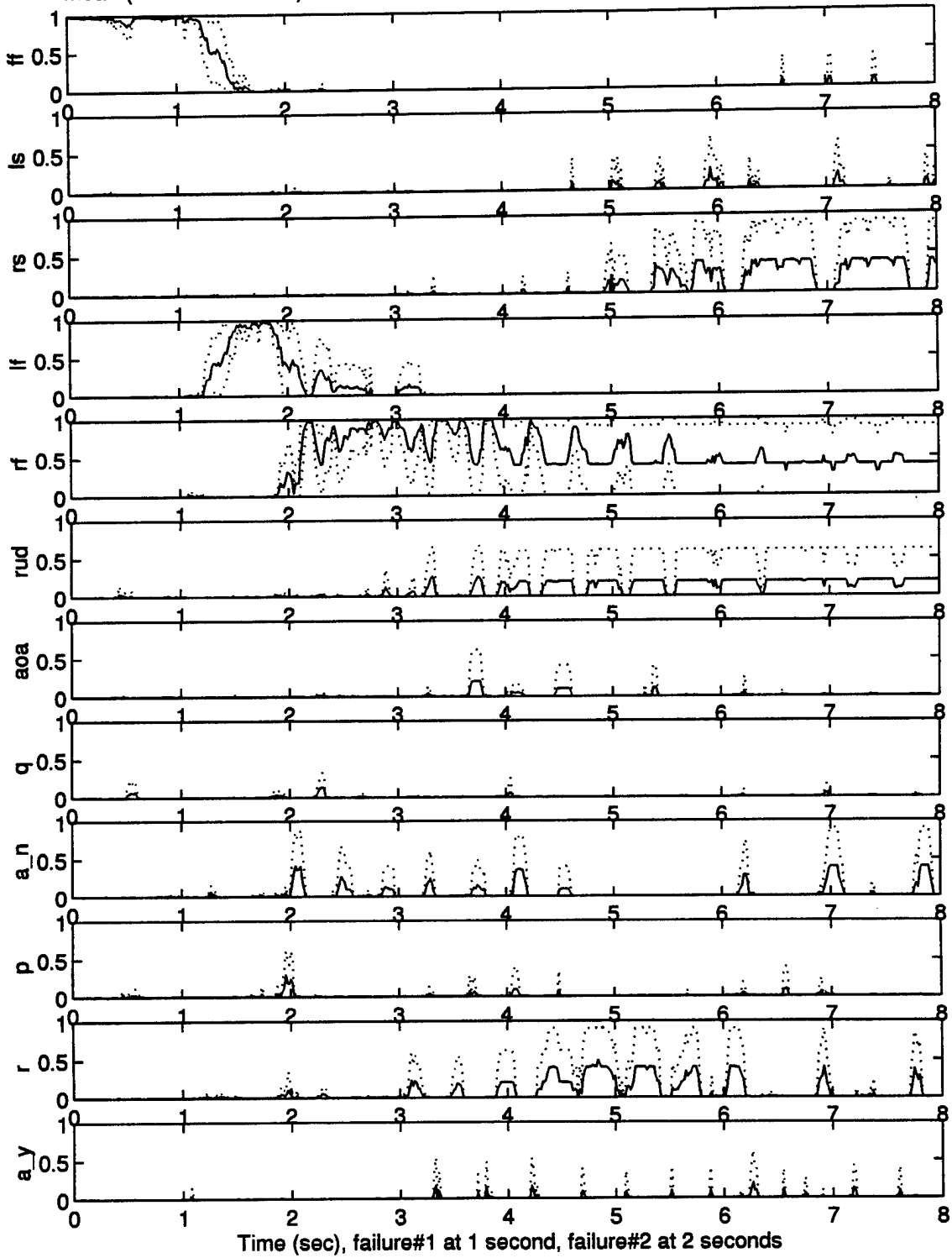
Mean (+/- One Std Dev) Dual-fail Probabilities of fail253.251 with reconfiguration: 10 runs



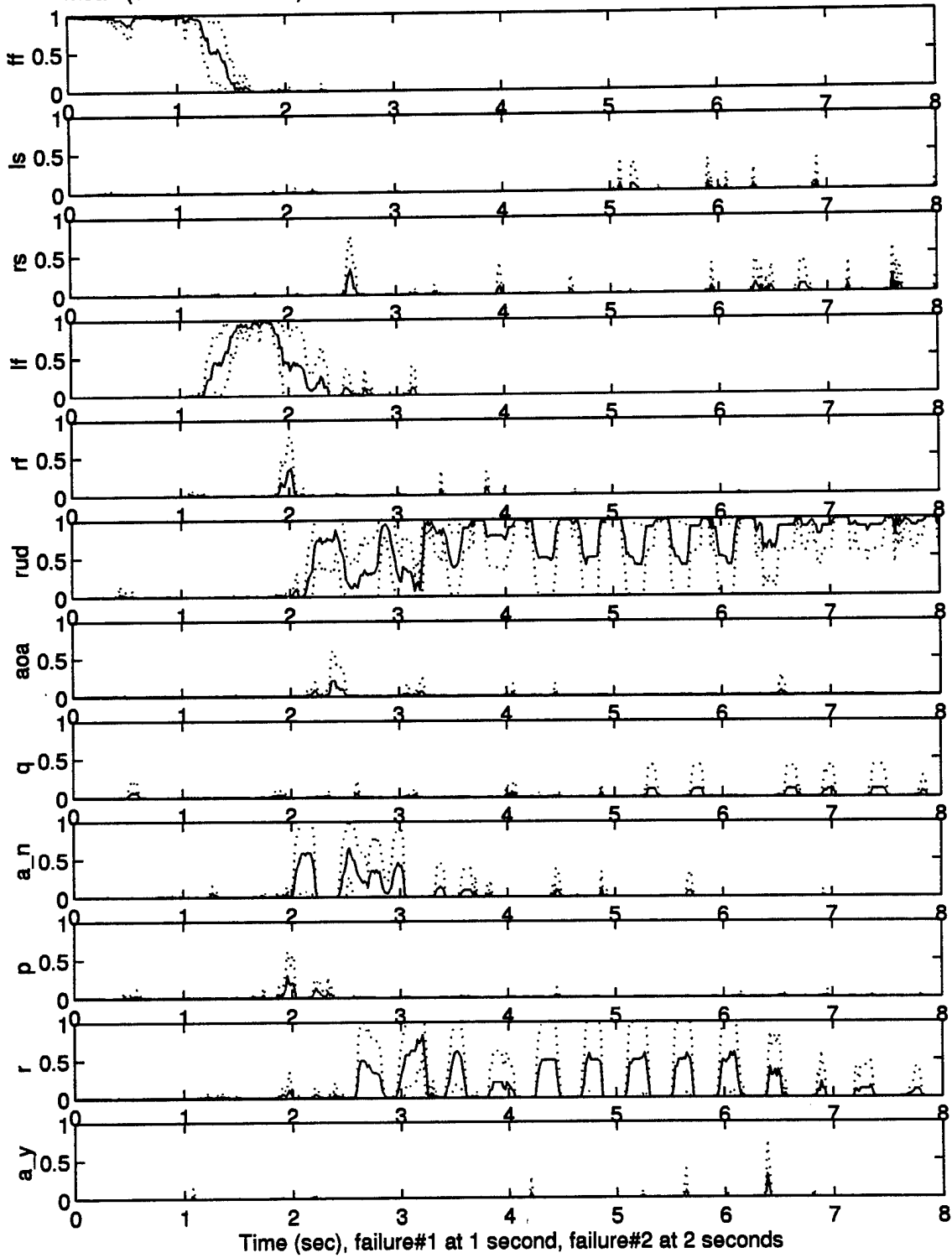
Mean (+/- One Std Dev) Dual-fail Probabilities of fail253.252 with reconfiguration: 10 runs



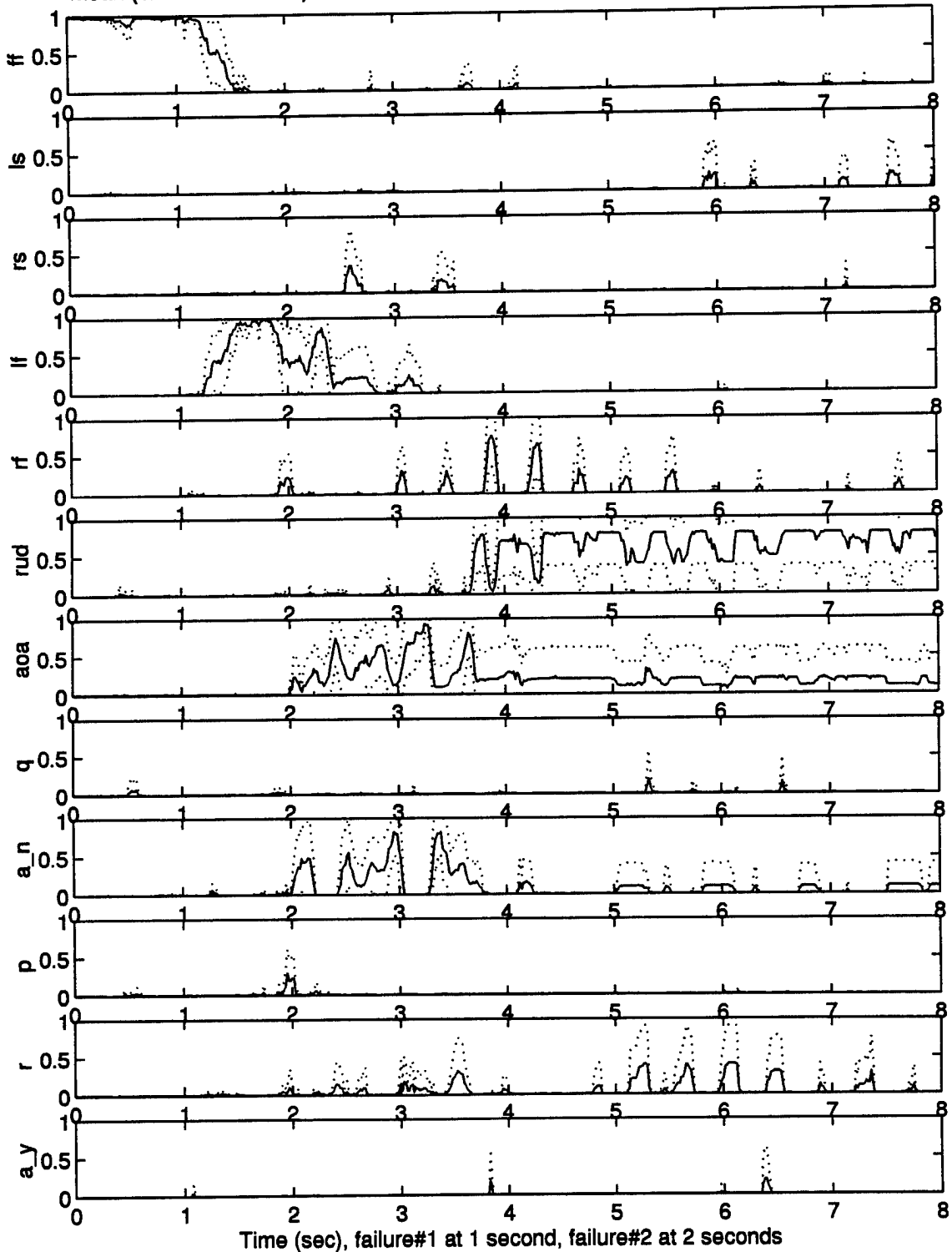
Mean (+/- One Std Dev) Dual-fail Probabilities of fail253.254 with reconfiguration: 10 runs



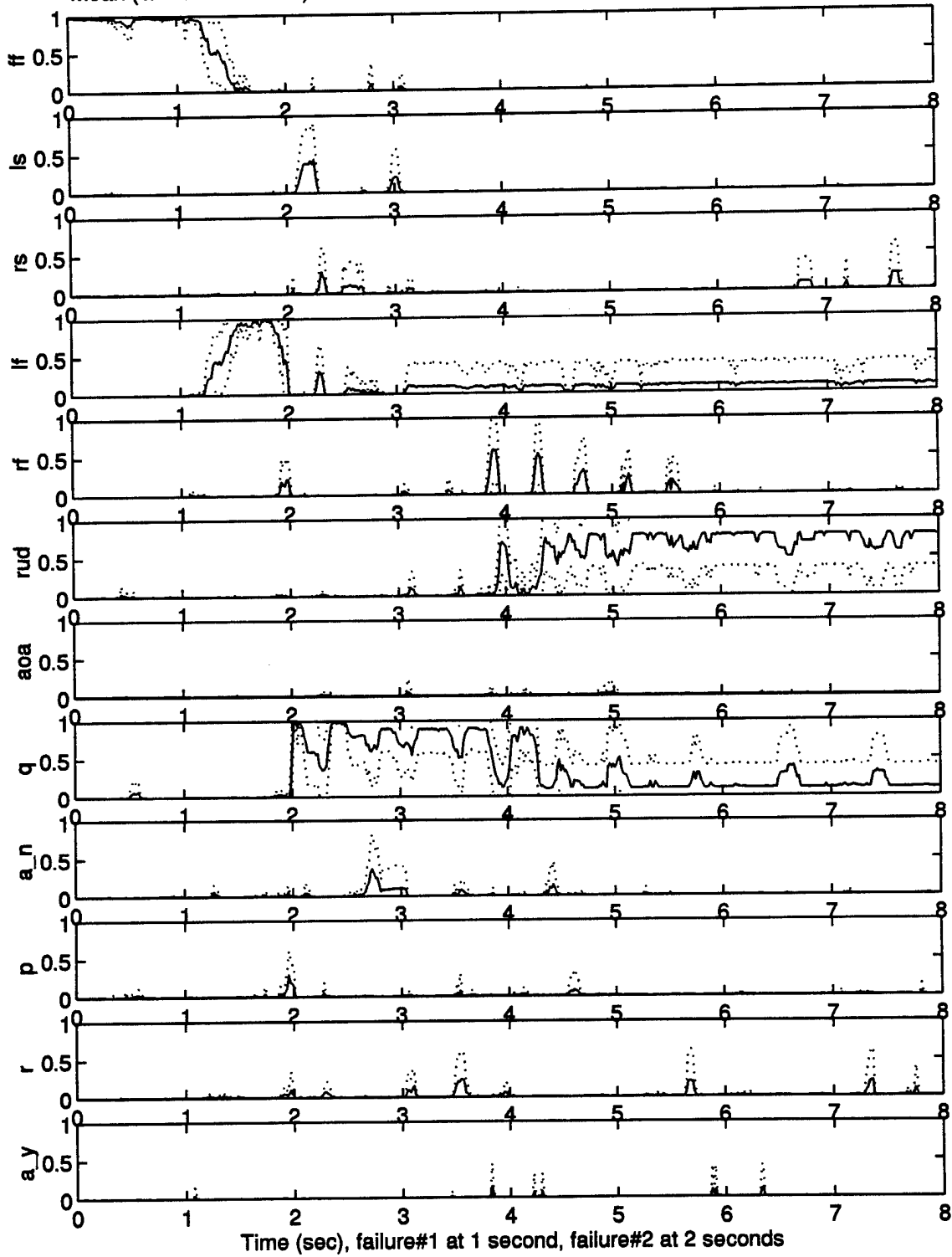
Mean (+/- One Std Dev) Dual-fail Probabilities of fail253.255 with reconfiguration: 10 runs



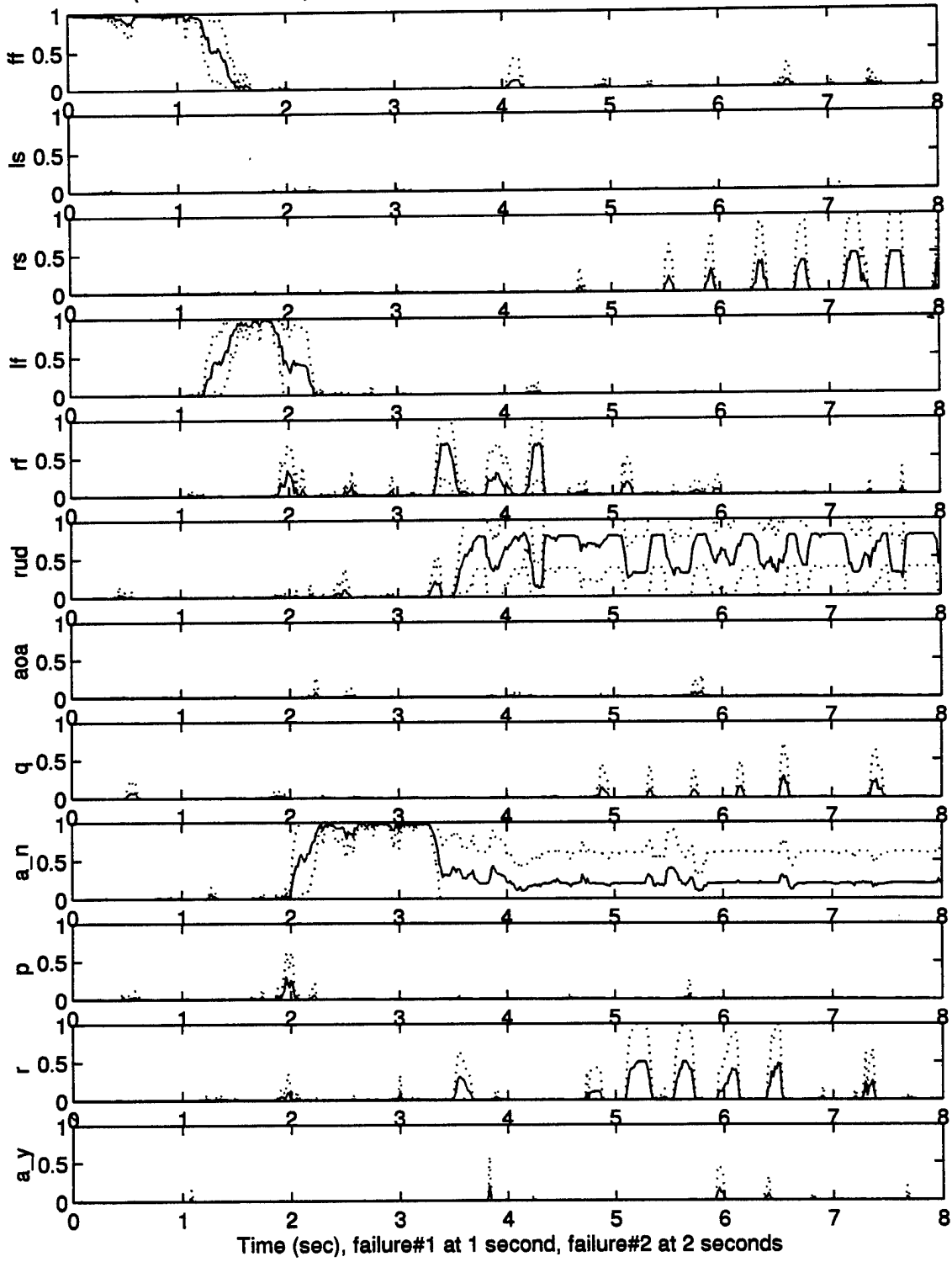
Mean (+/- One Std Dev) Dual-fail Probabilities of fail253.06 with reconfiguration: 10 runs



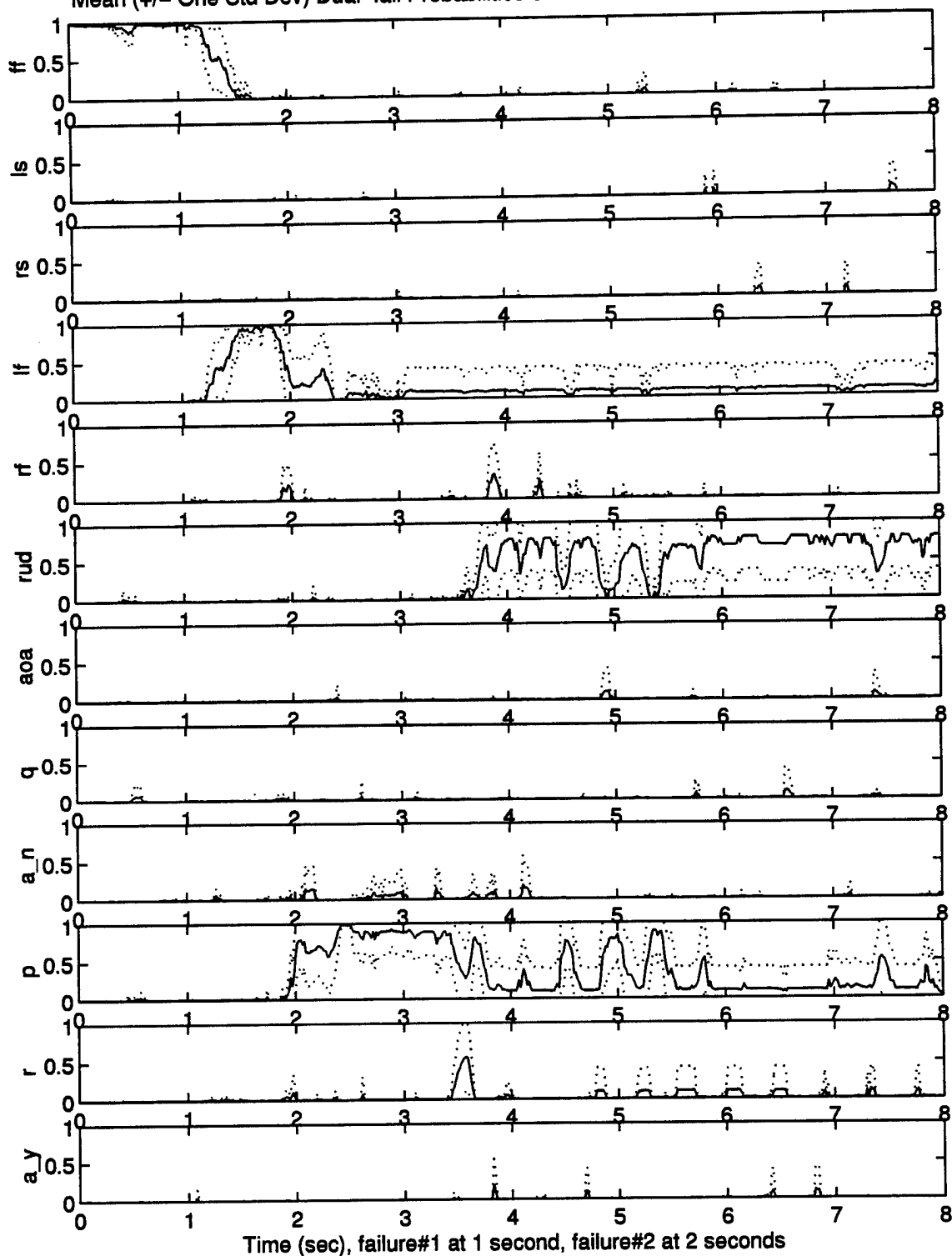
Mean (+/- One Std Dev) Dual-fail Probabilities of fail253.07 with reconfiguration: 10 runs



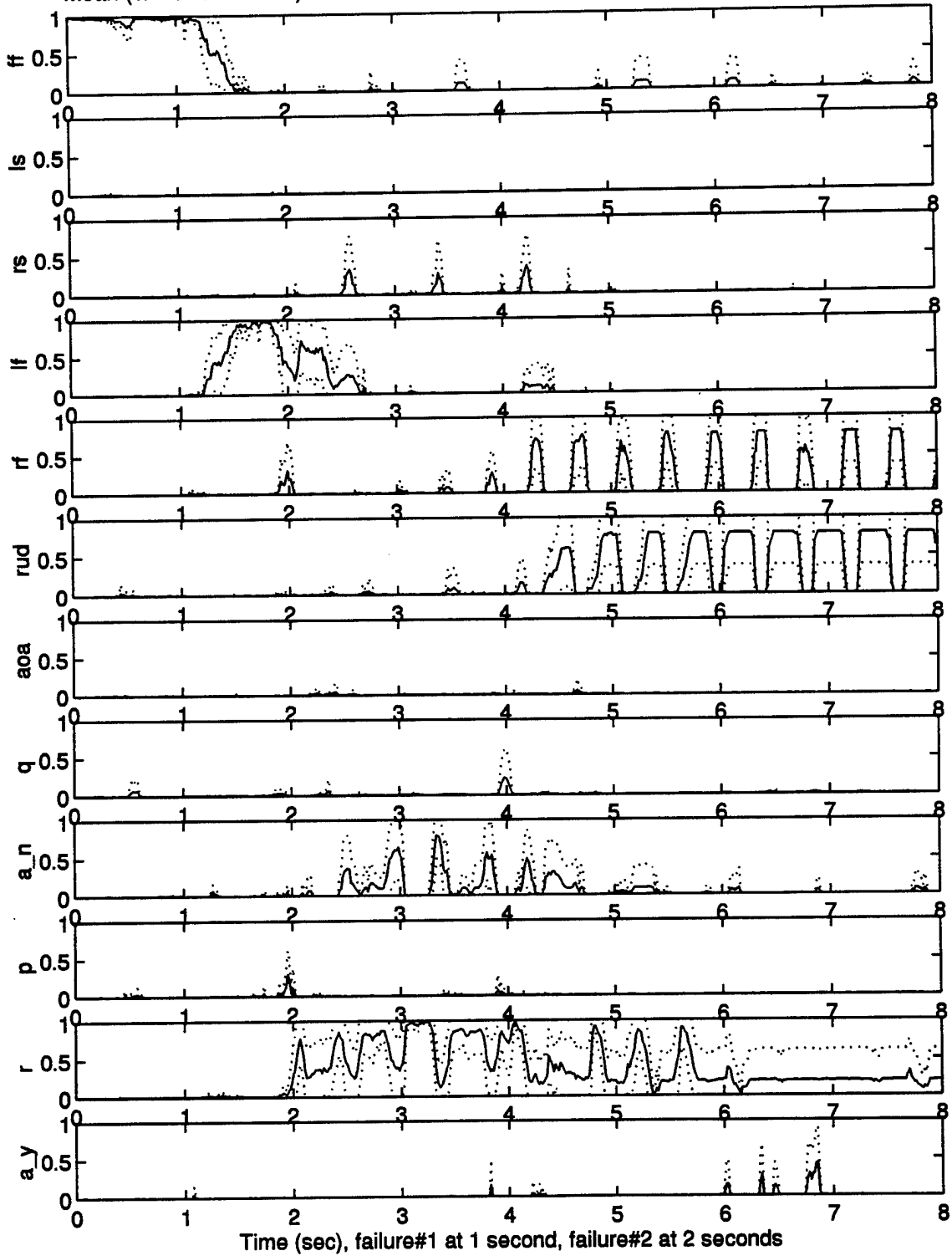
Mean (+/- One Std Dev) Dual-fail Probabilities of fail253.08 with reconfiguration: 10 runs



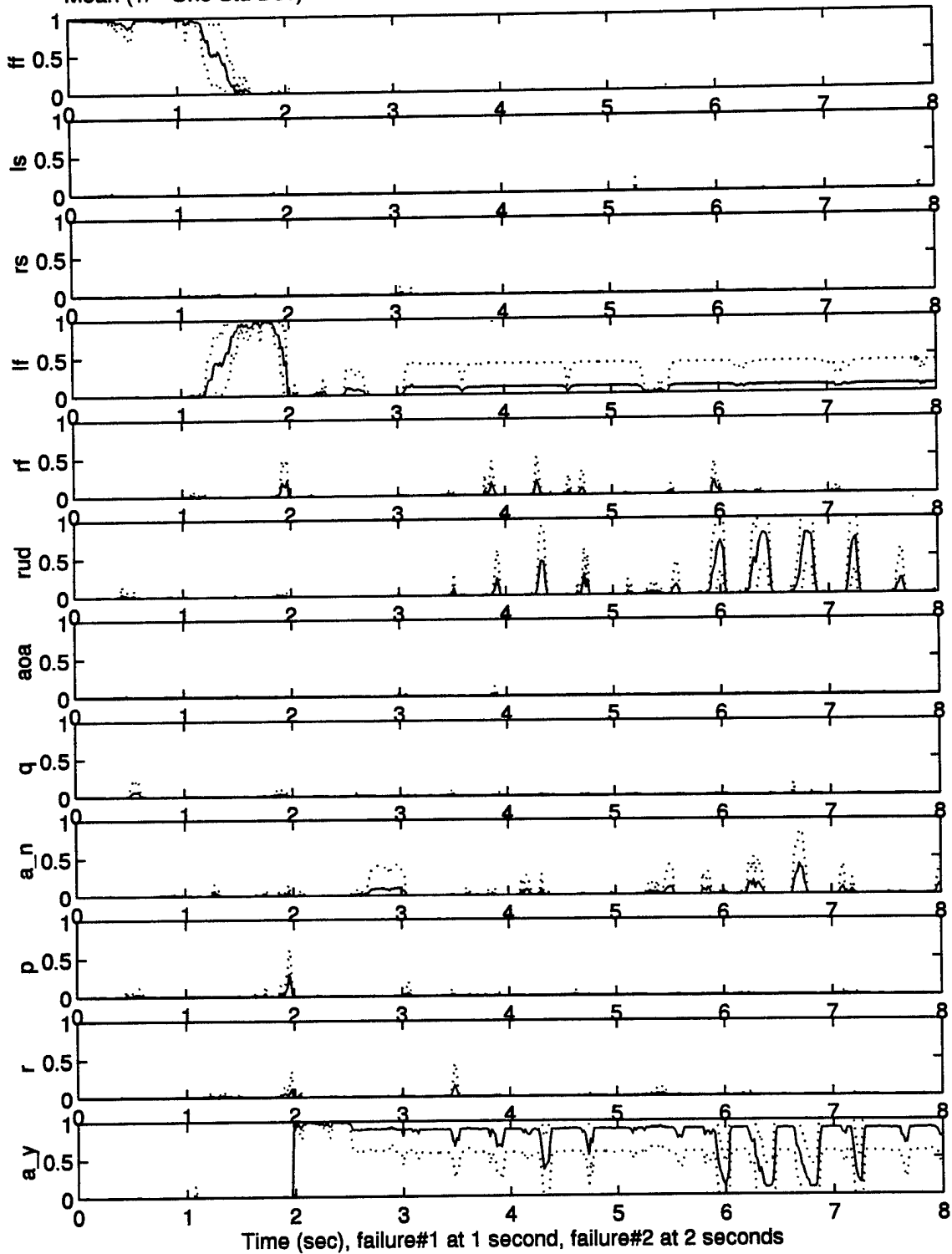
Mean (+/- One Std Dev) Dual-fail Probabilities of fail253.09 with reconfiguration: 10 runs



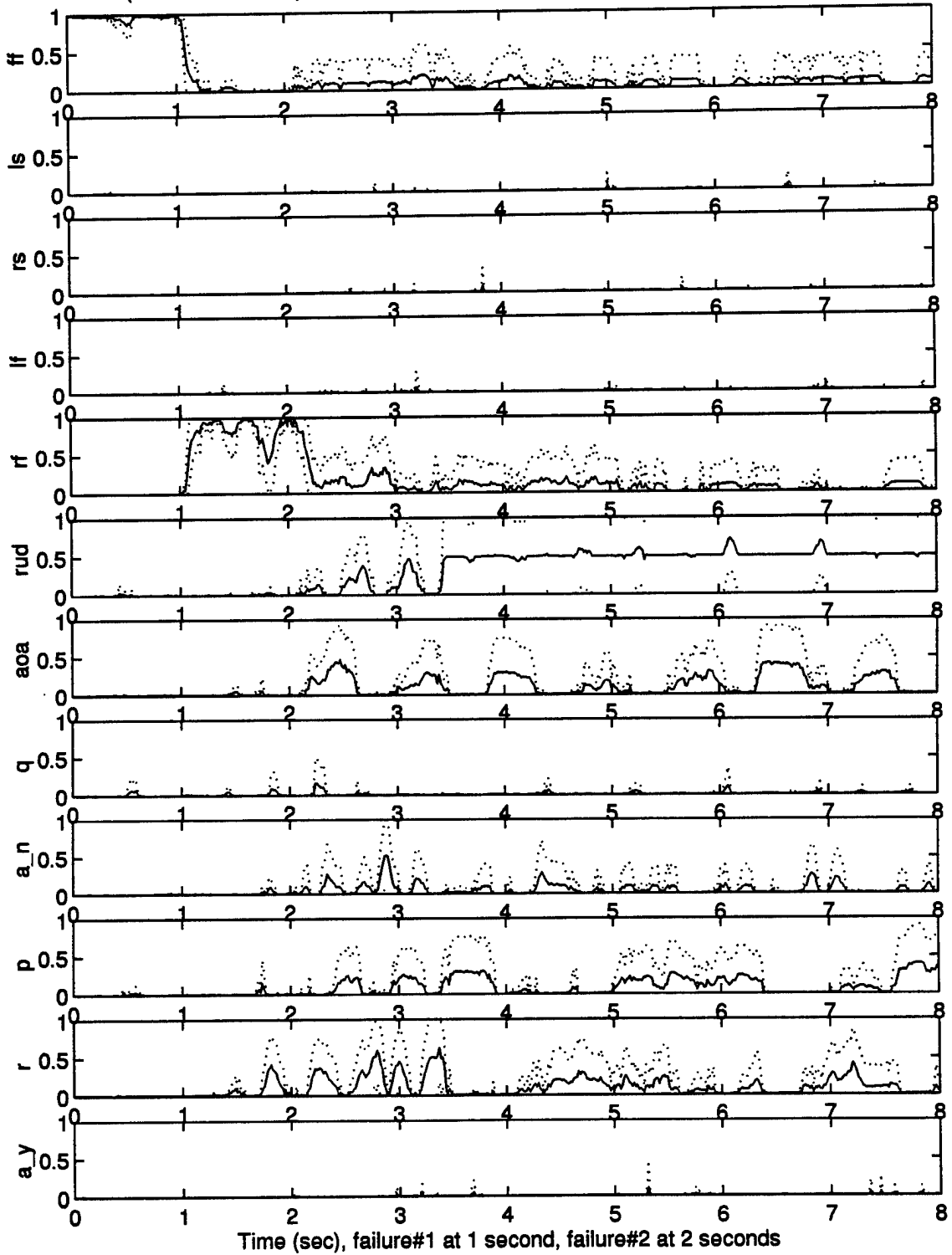
Mean (+/- One Std Dev) Dual-fail Probabilities of fail253.010 with reconfiguration: 10 runs



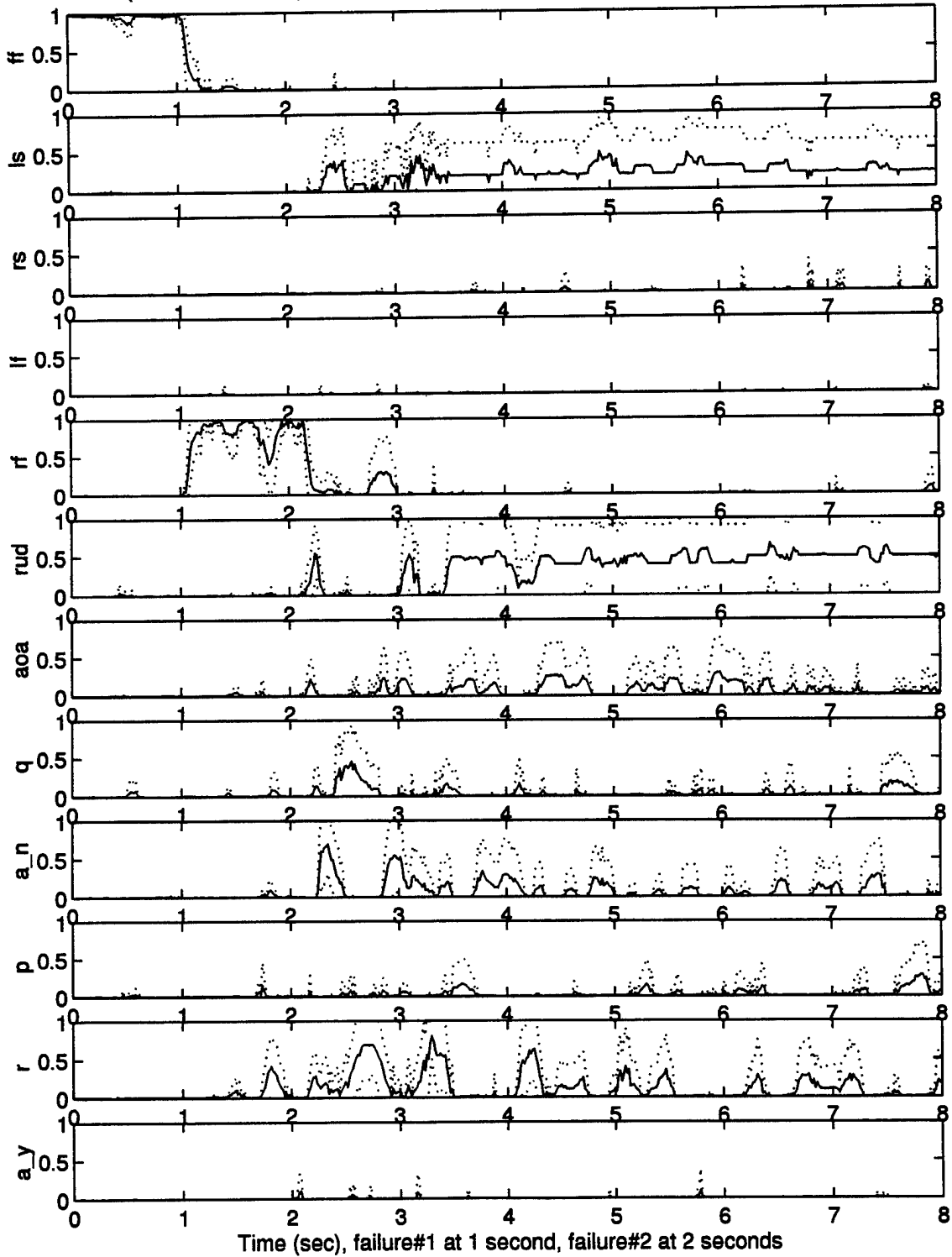
Mean (+/- One Std Dev) Dual-fail Probabilities of fail253.011 with reconfiguration: 10 runs



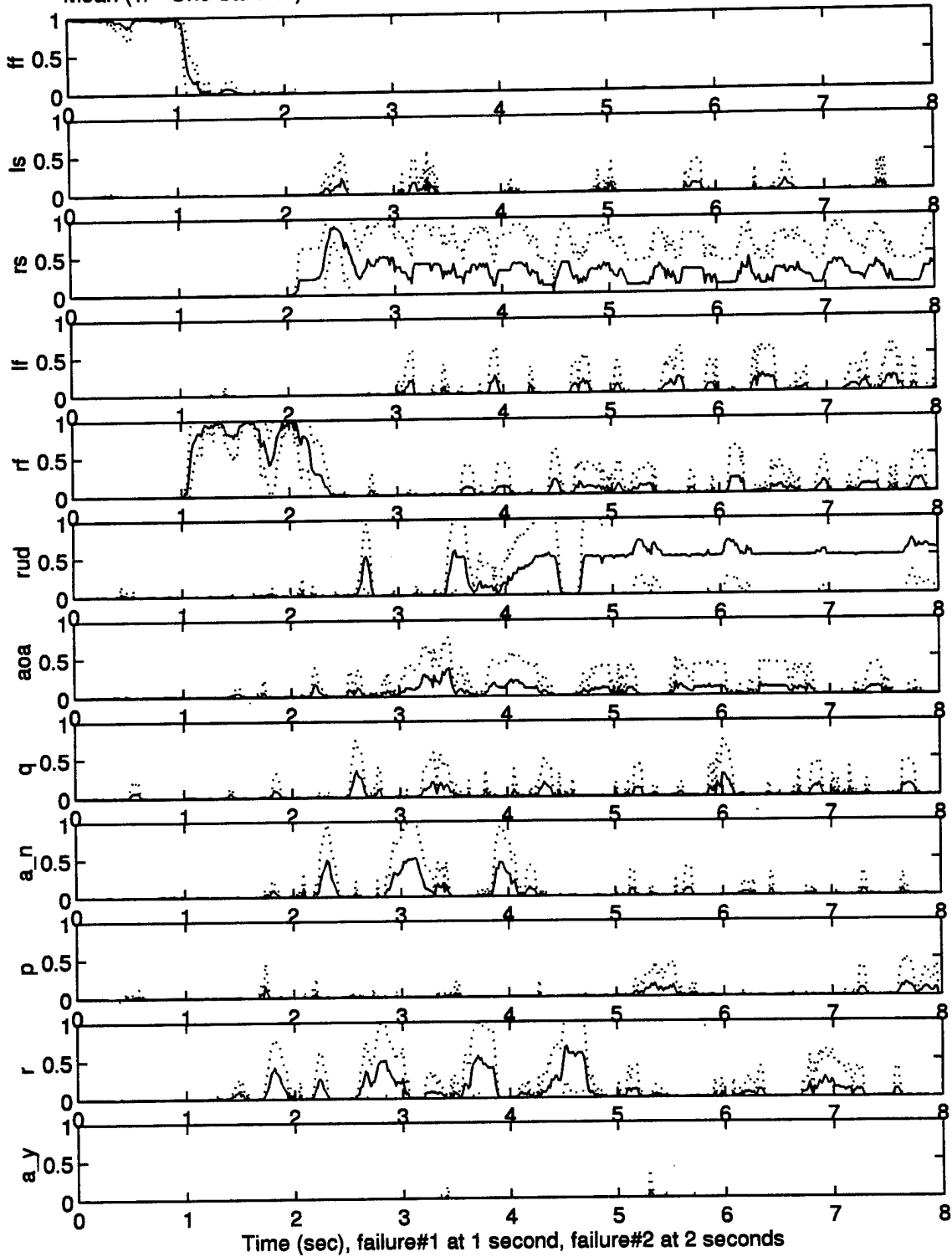
Mean (+/- One Std Dev) Dual-fail Probabilities of fail254.250 with reconfiguration: 10 runs



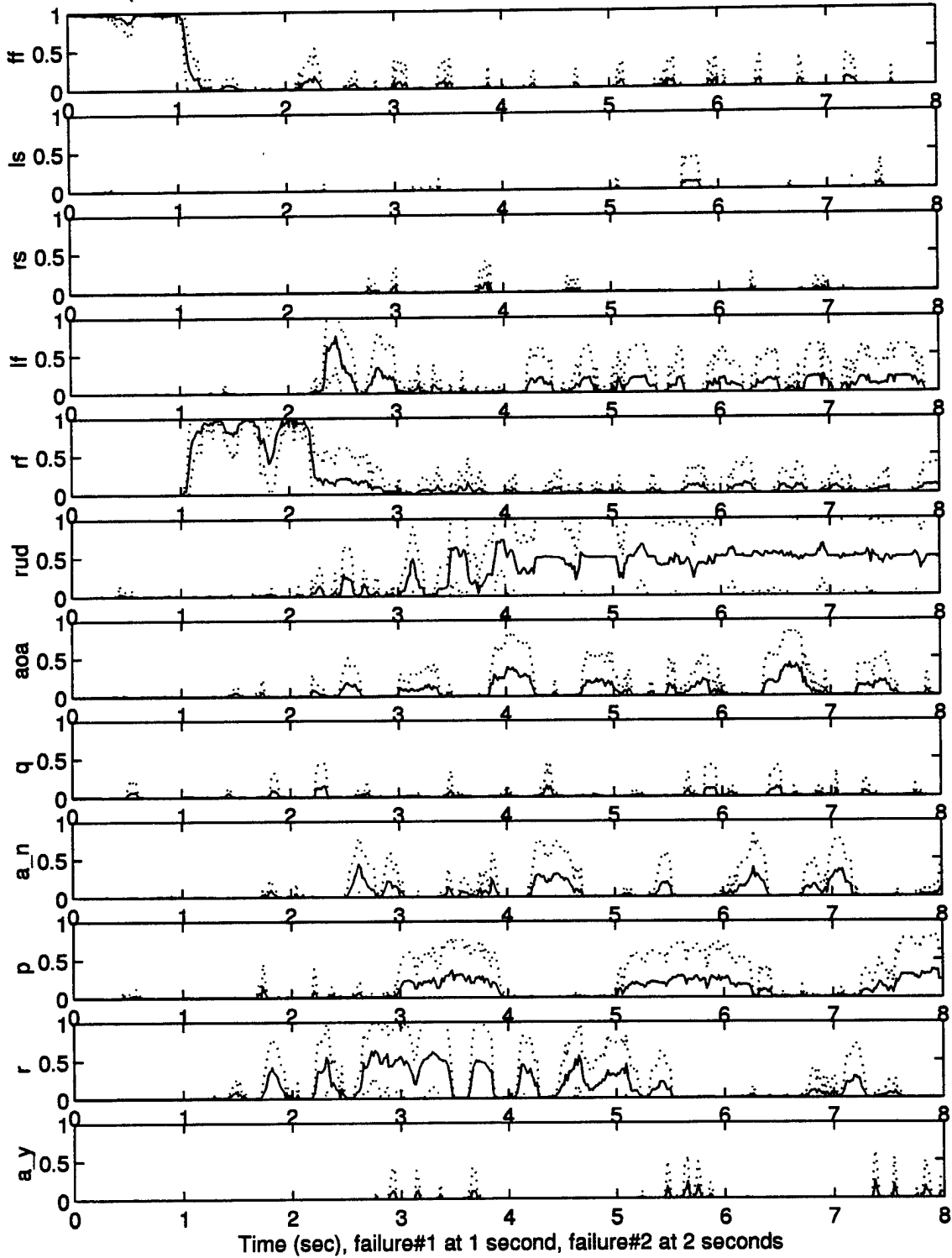
Mean (+/- One Std Dev) Dual-fail Probabilities of fail254.251 with reconfiguration: 10 runs



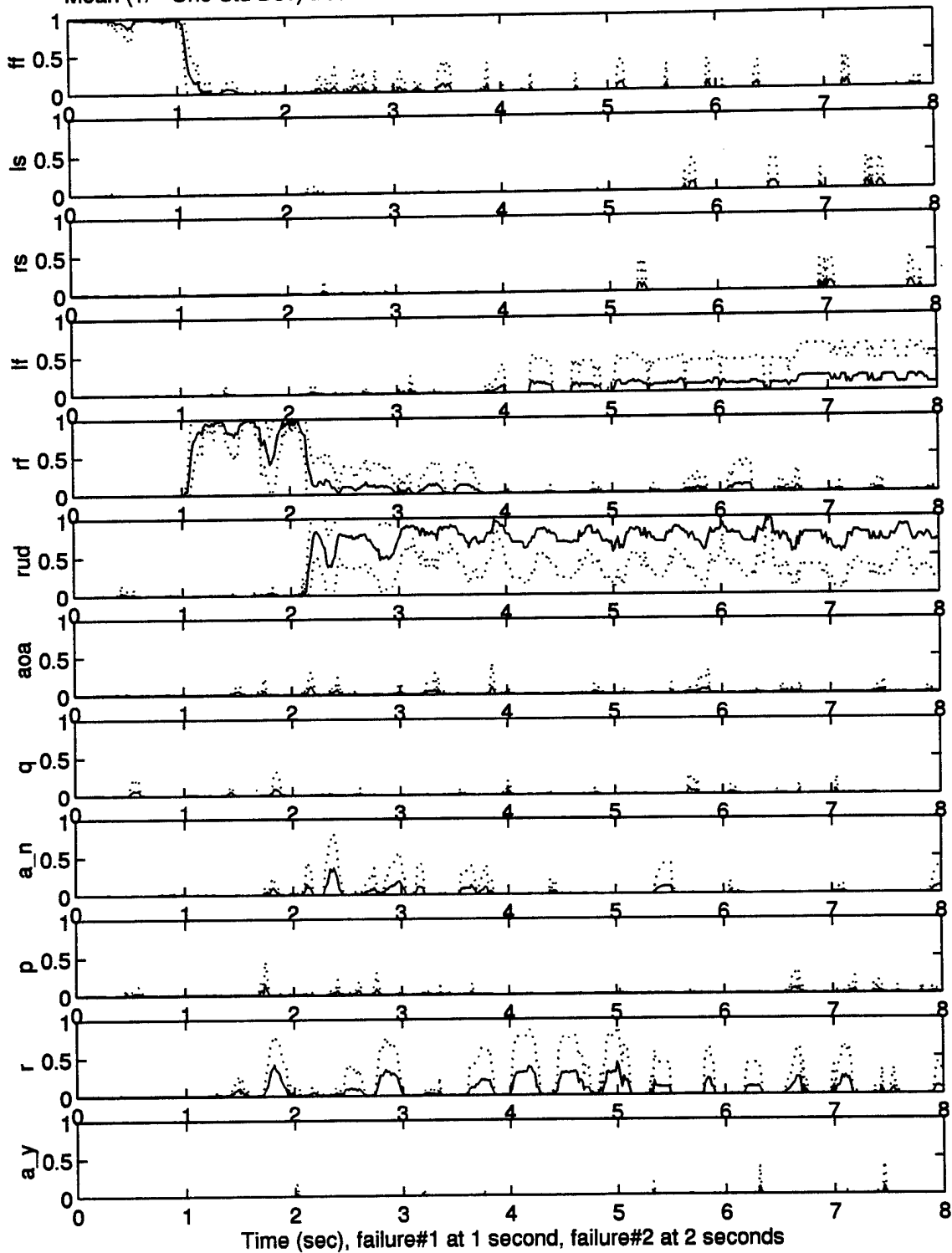
Mean (+/- One Std Dev) Dual-fail Probabilities of fail254.252 with reconfiguration: 10 runs



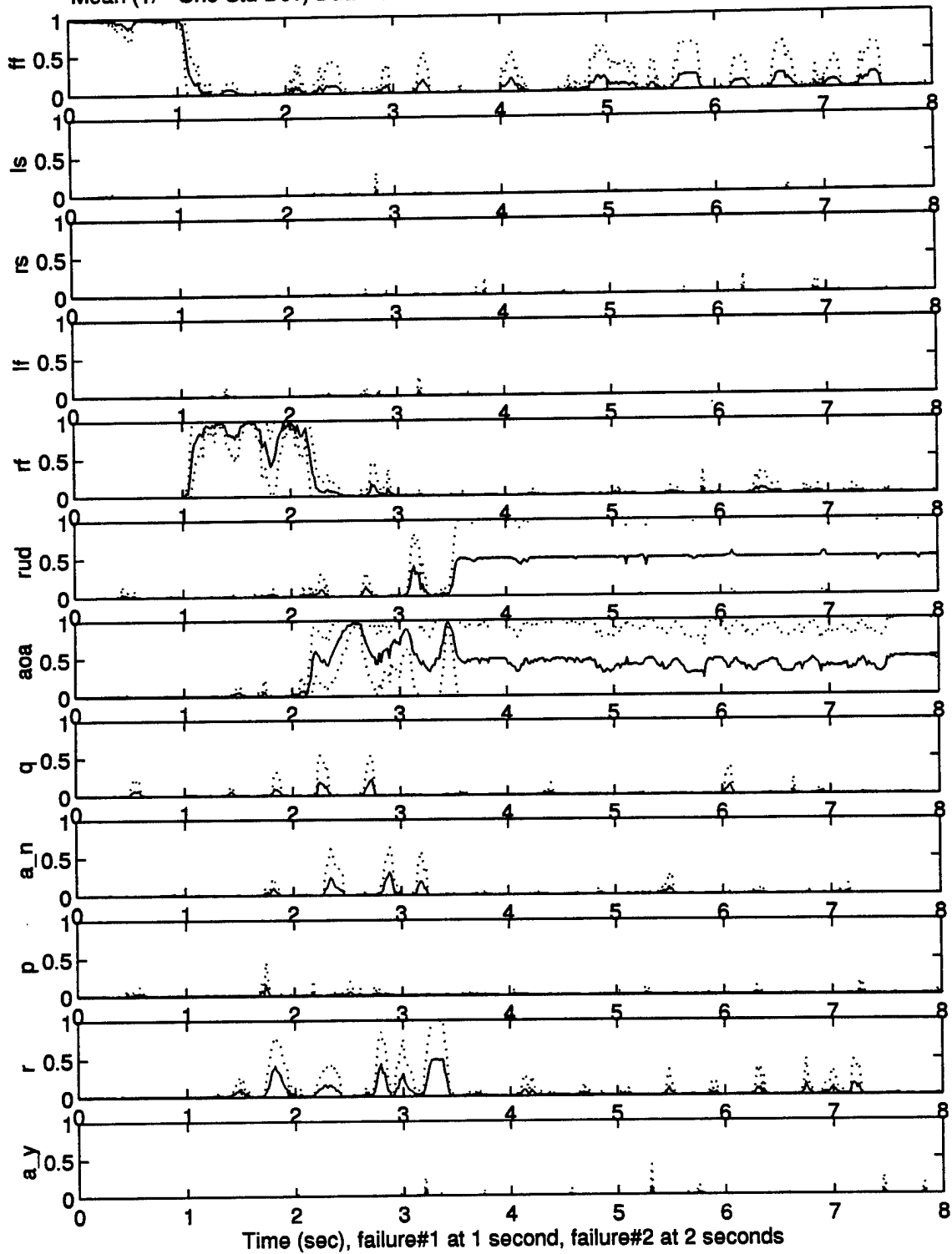
Mean (+/- One Std Dev) Dual-fail Probabilities of fail254.253 with reconfiguration: 10 runs



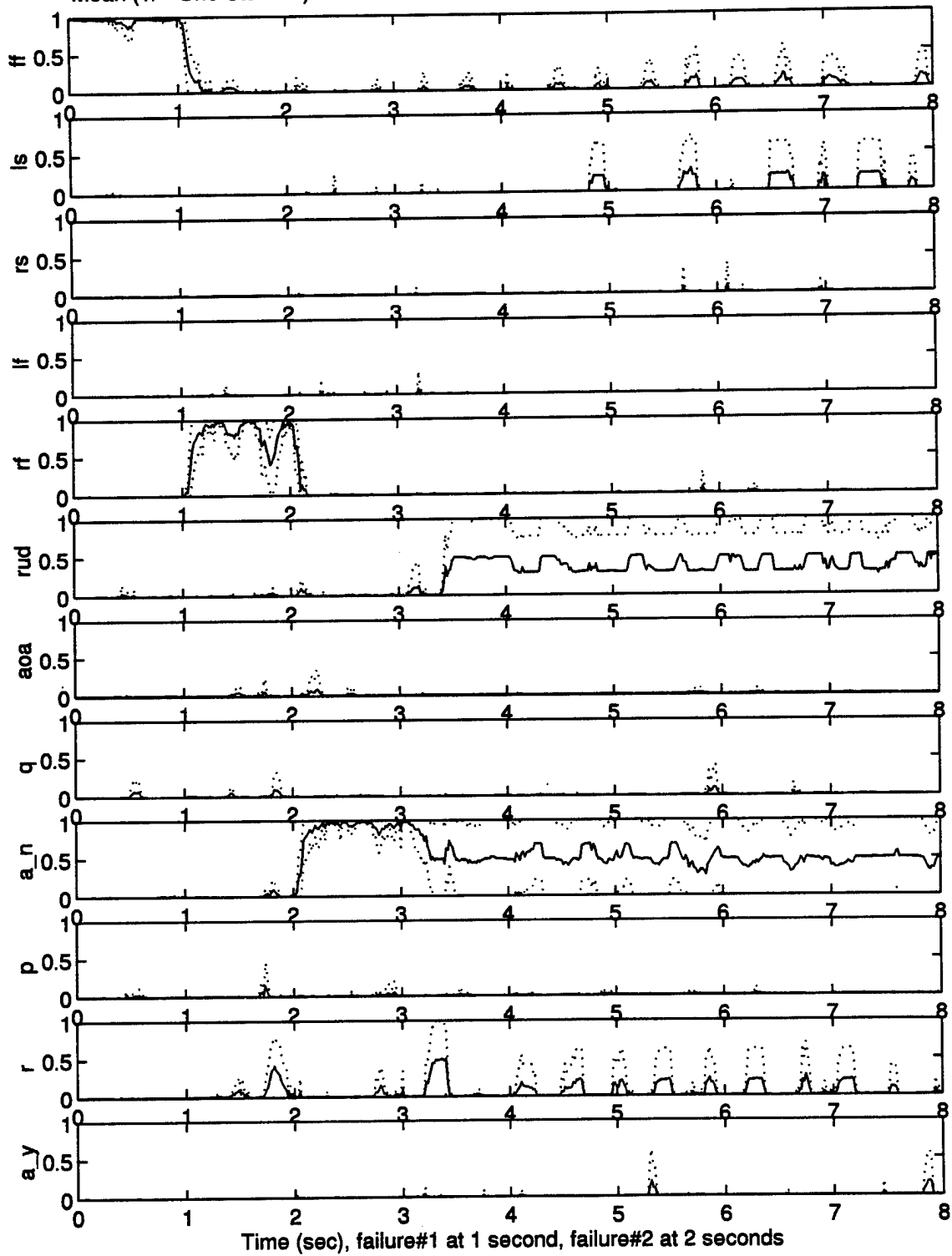
Mean (+/- One Std Dev) Dual-fail Probabilities of fail254.255 with reconfiguration: 10 runs



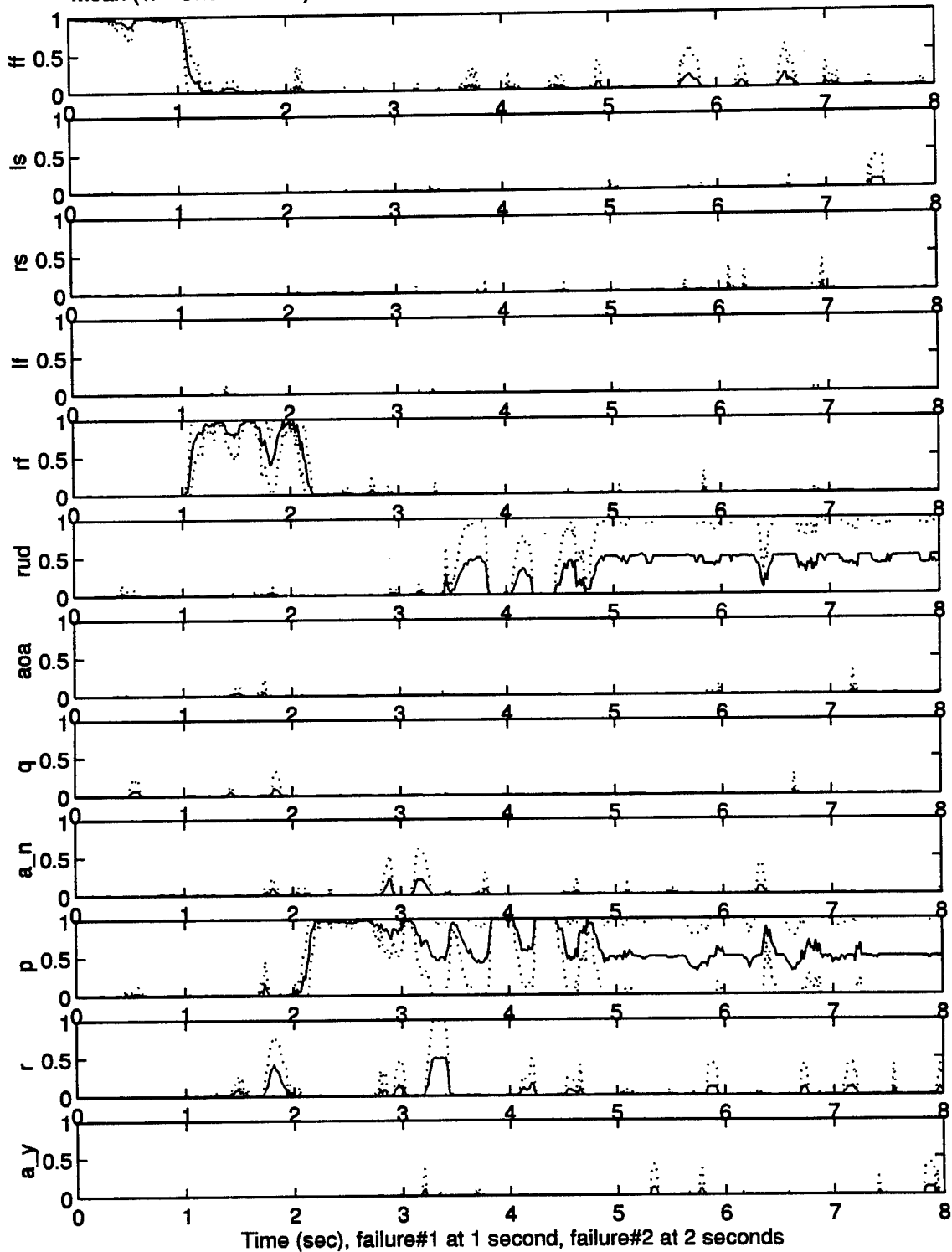
Mean (+/- One Std Dev) Dual-fail Probabilities of fail254.06 with reconfiguration: 10 runs



Mean (+/- One Std Dev) Dual-fail Probabilities of fail254.08 with reconfiguration: 10 runs

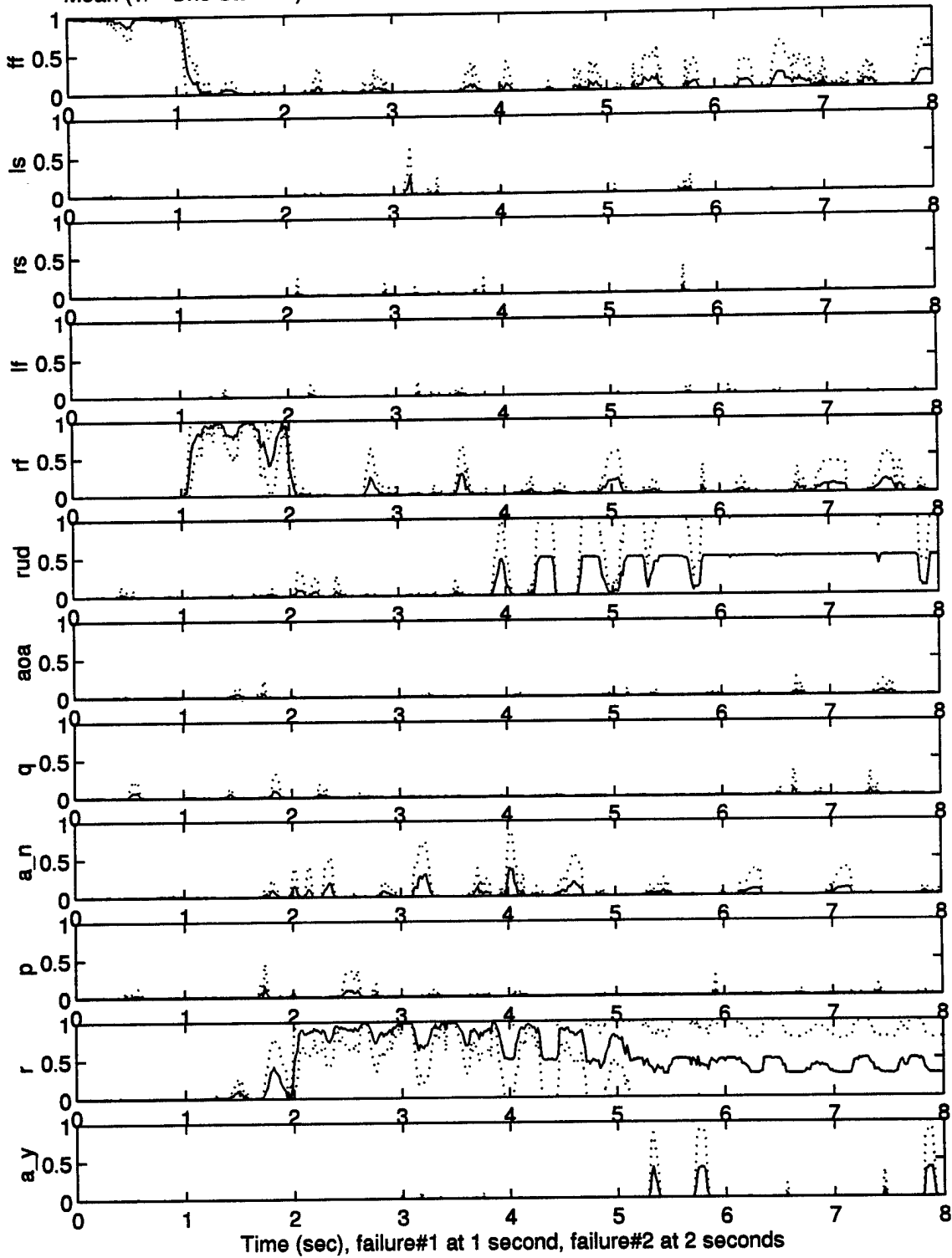


Mean (+/- One Std Dev) Dual-fail Probabilities of fail254.09 with reconfiguration: 10 runs

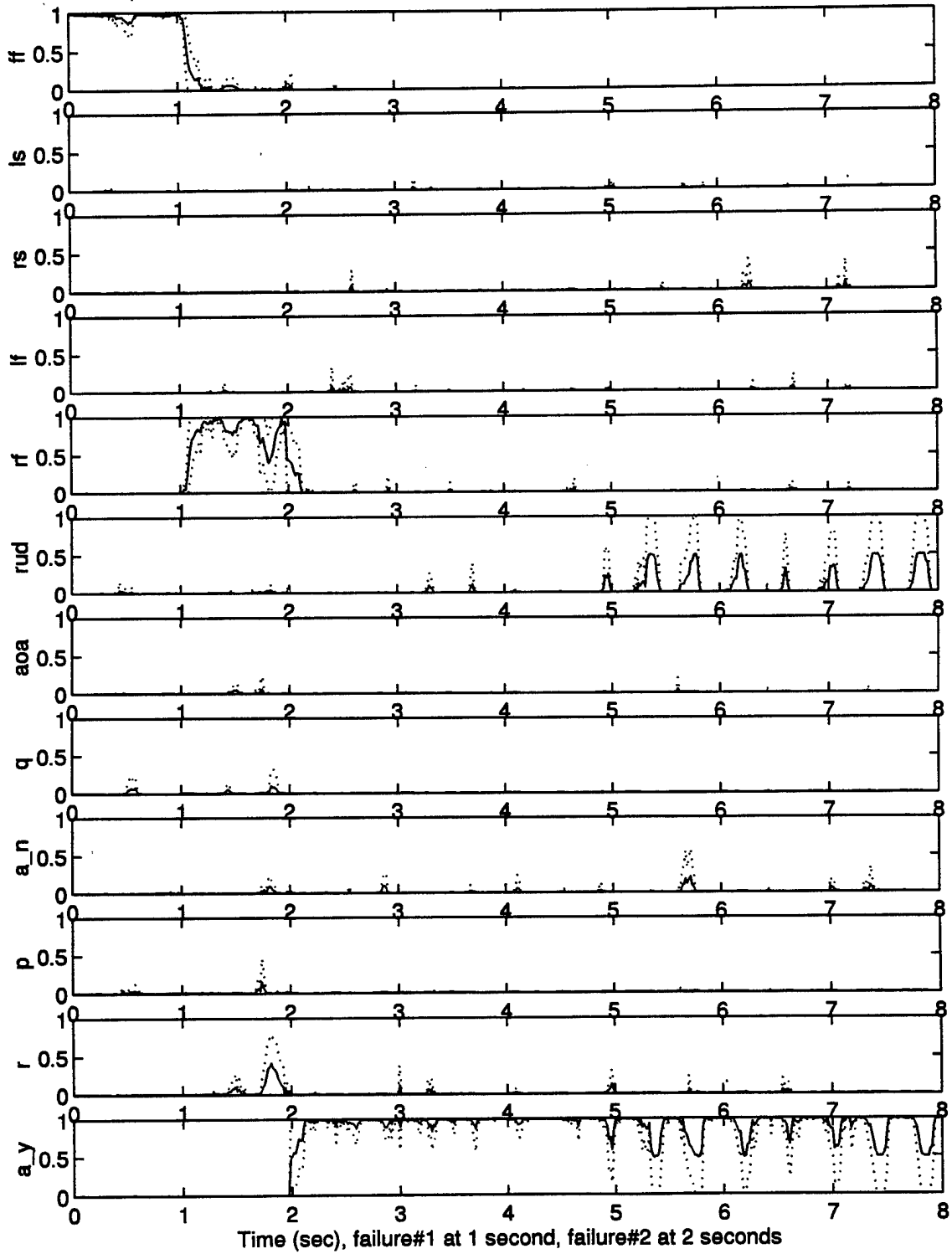


Time (sec), failure#1 at 1 second, failure#2 at 2 seconds

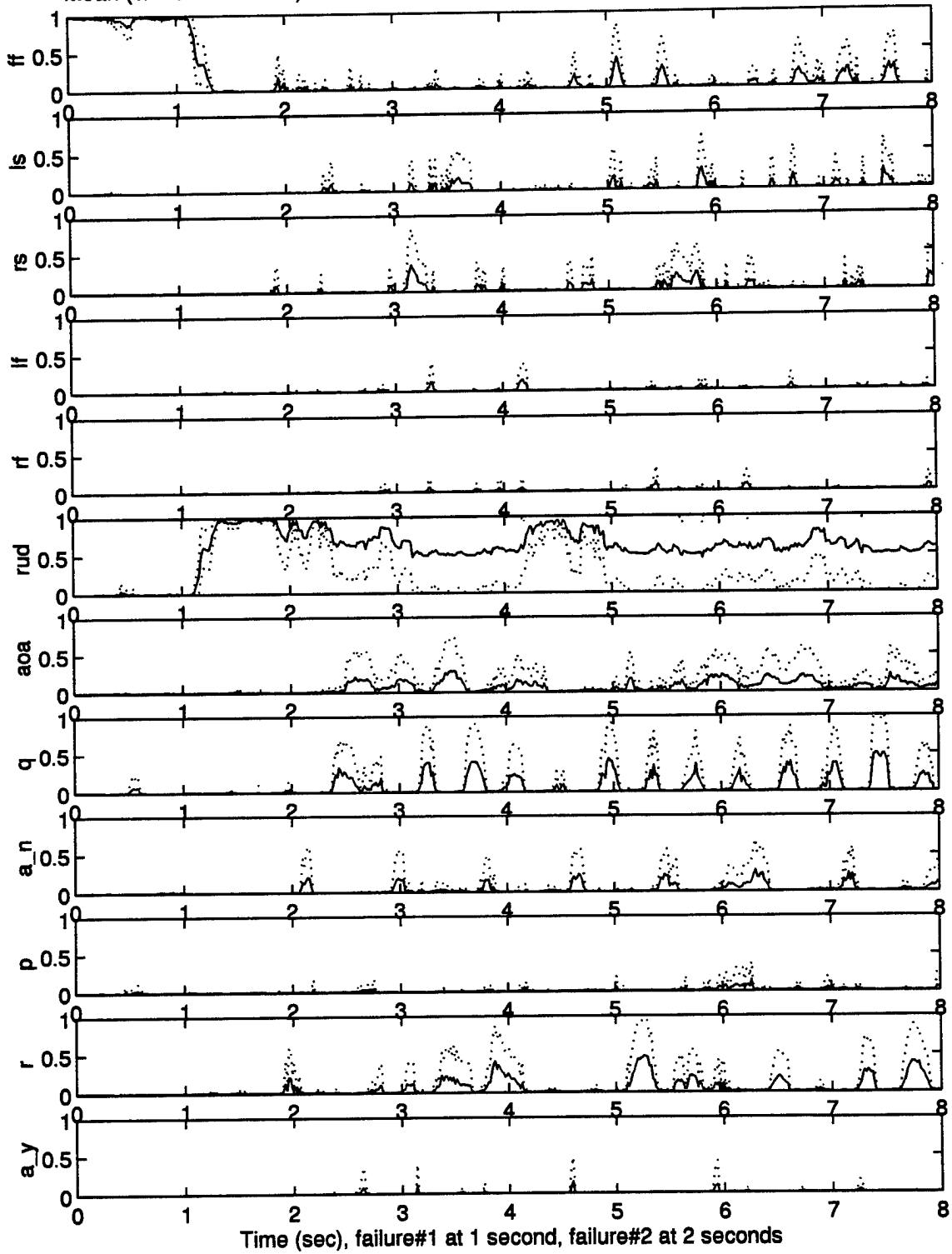
Mean (+/- One Std Dev) Dual-fail Probabilities of fail254.010 with reconfiguration: 10 runs



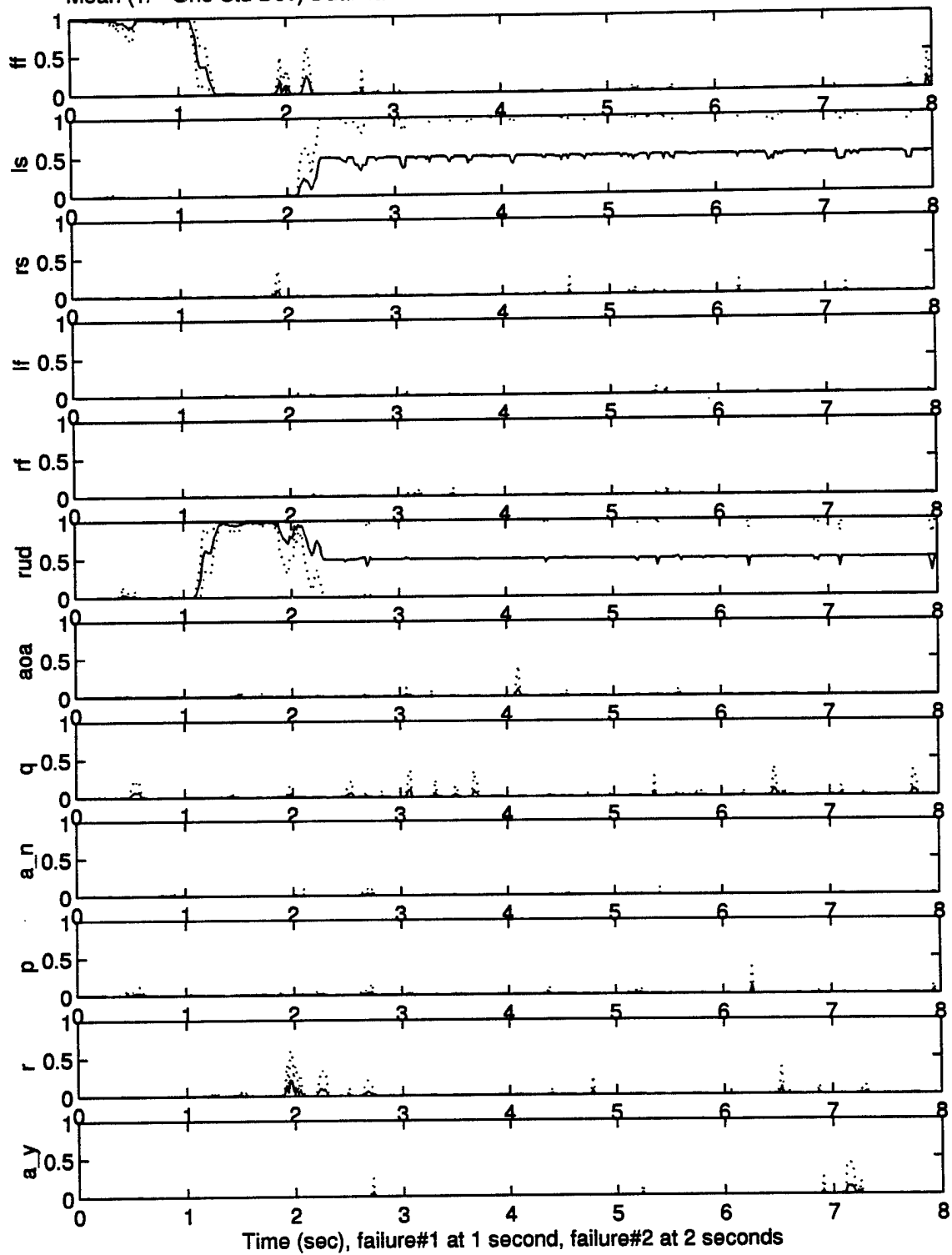
Mean (+/- One Std Dev) Dual-fail Probabilities of fail254.011 with reconfiguration: 10 runs



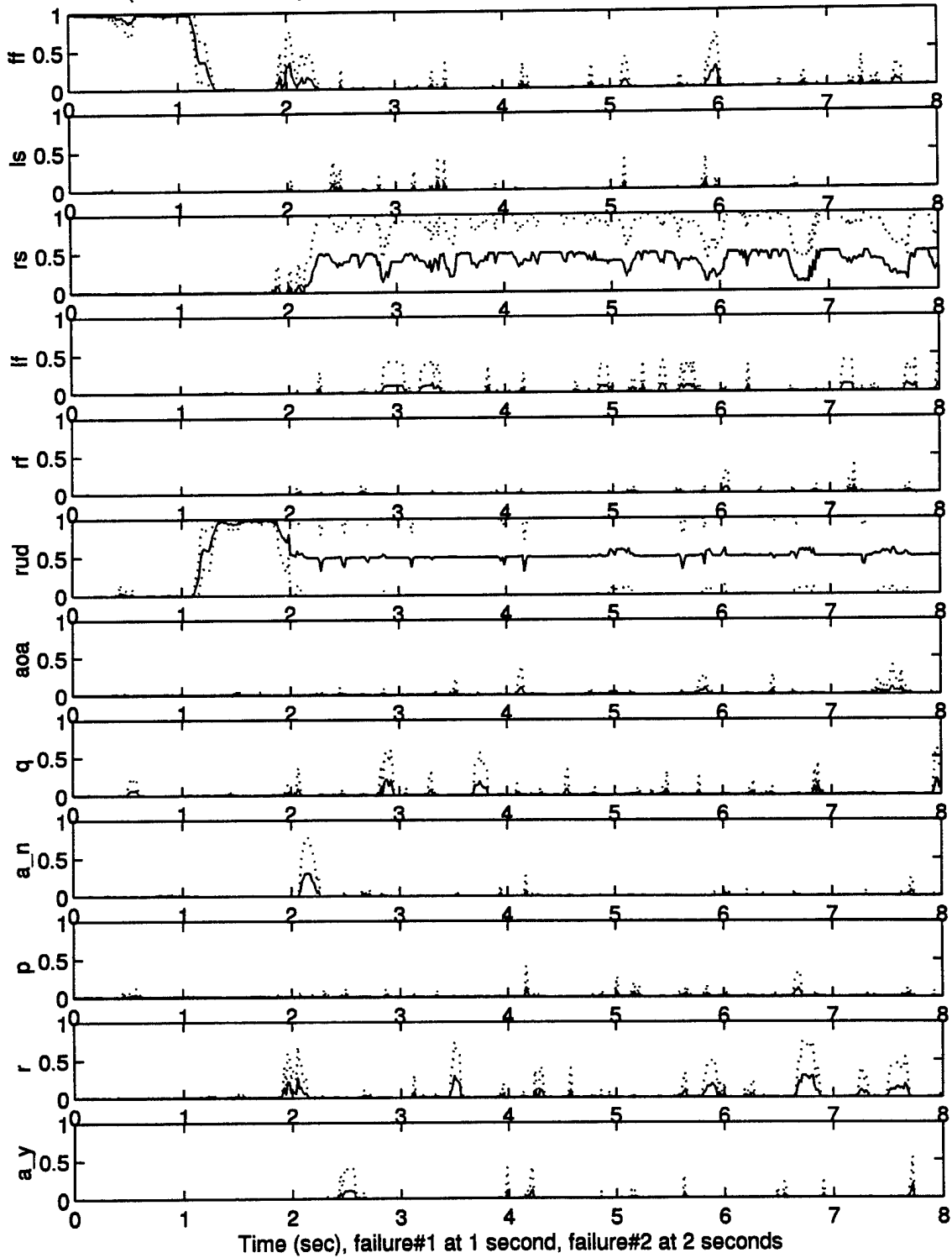
Mean (+/- One Std Dev) Dual-fail Probabilities of fail255.250 with reconfiguration: 10 runs



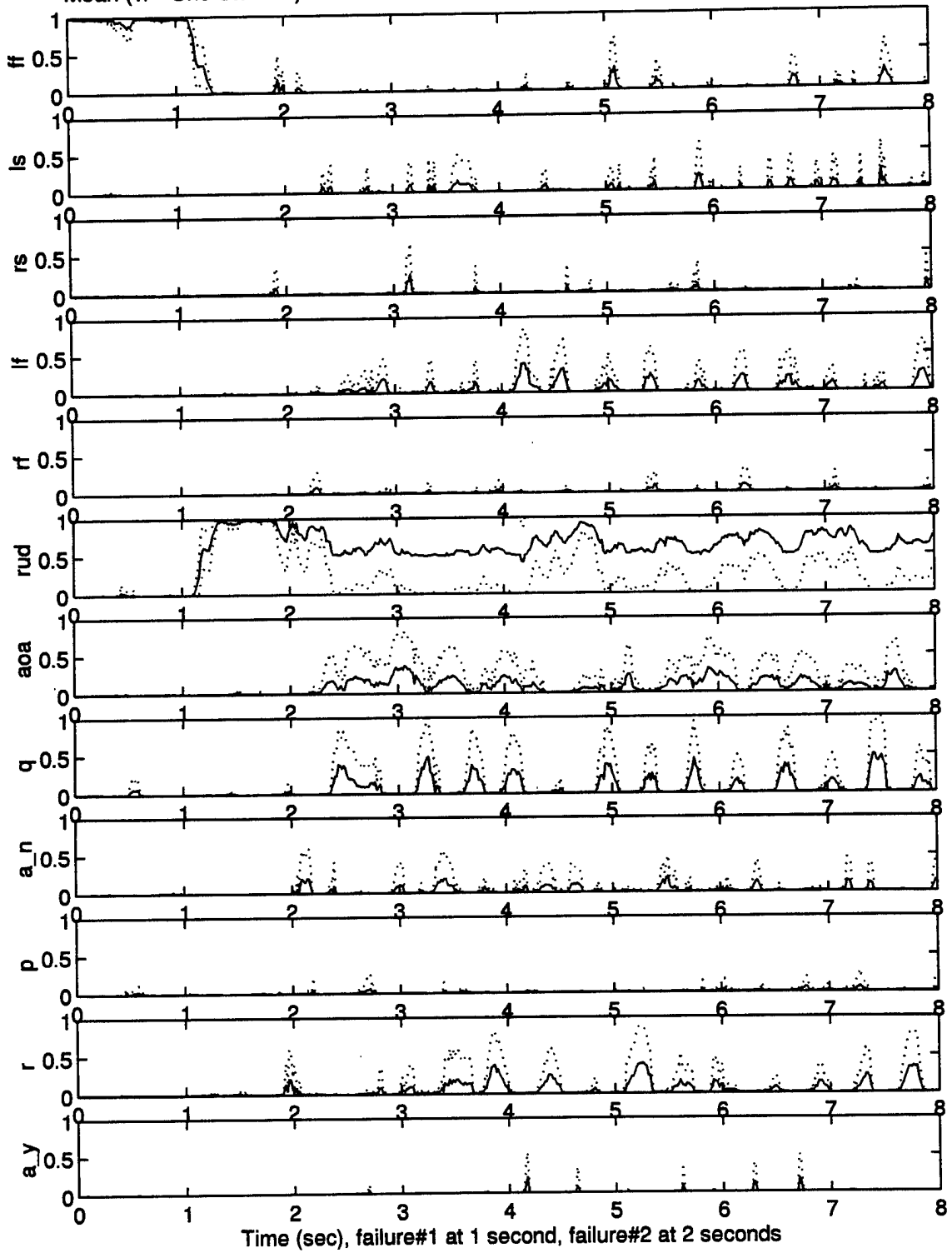
Mean (+/- One Std Dev) Dual-fail Probabilities of fail255.251 with reconfiguration: 10 runs



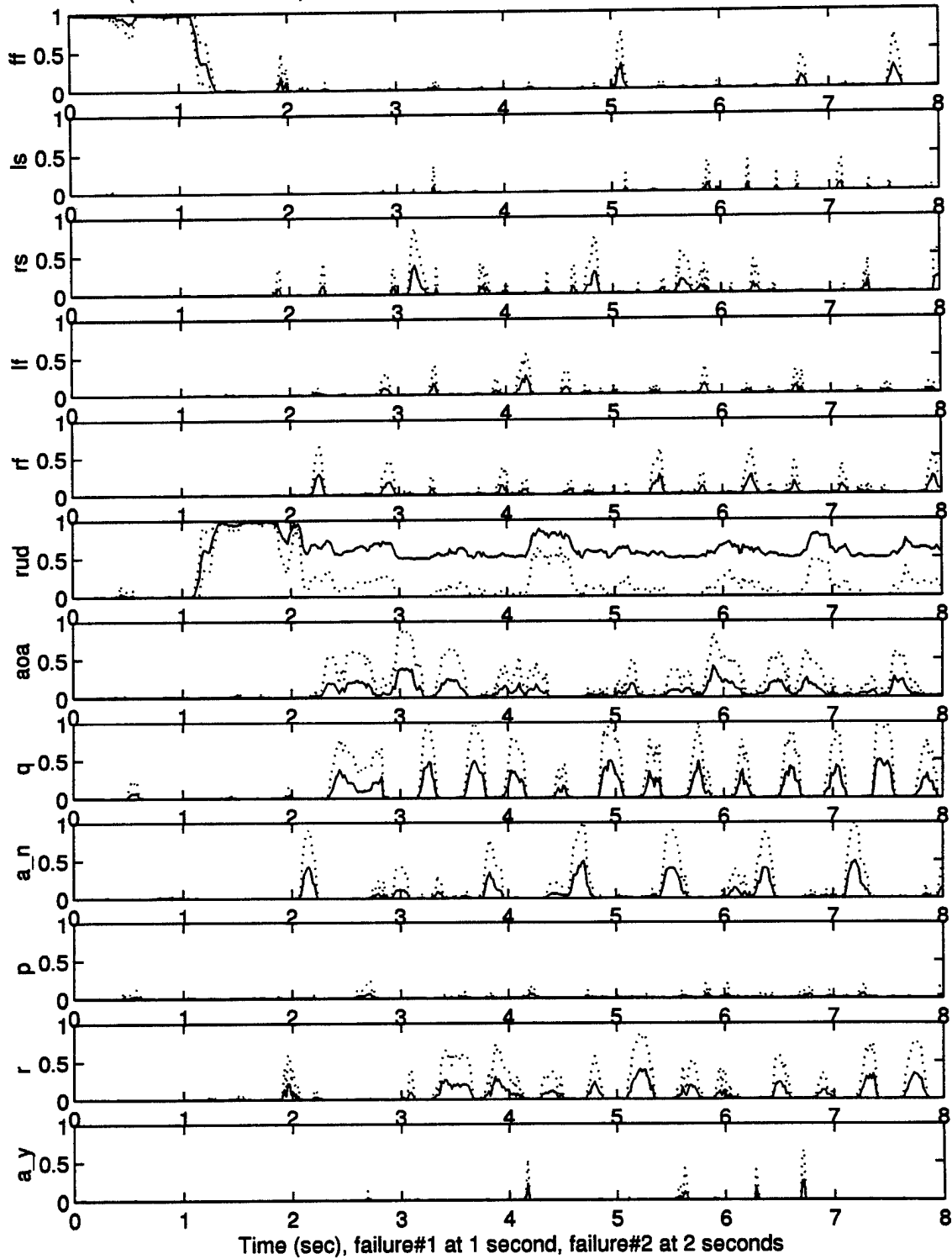
Mean (+/- One Std Dev) Dual-fail Probabilities of fail255.252 with reconfiguration: 10 runs



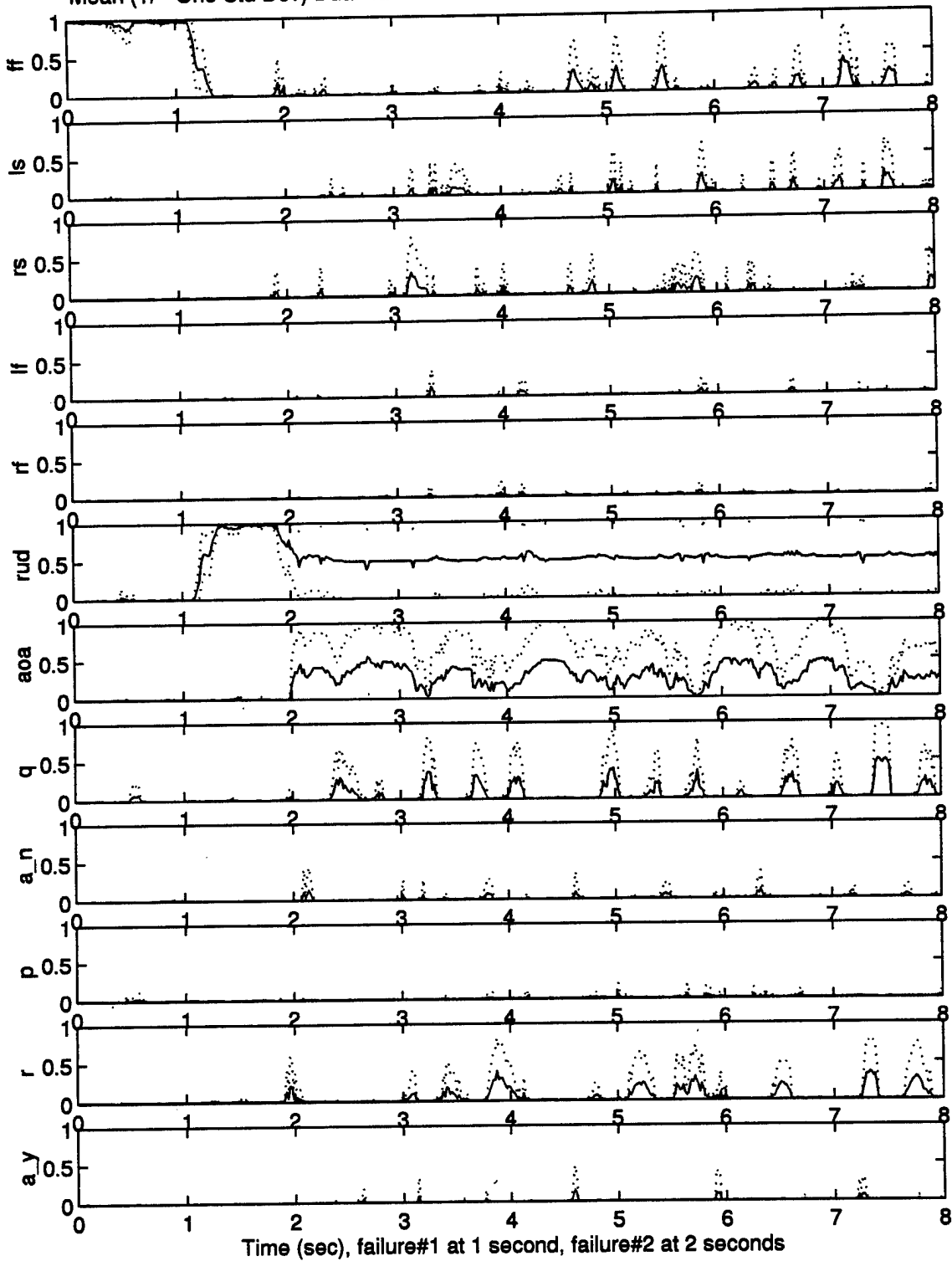
Mean (+/- One Std Dev) Dual-fail Probabilities of fail255.253 with reconfiguration: 10 runs



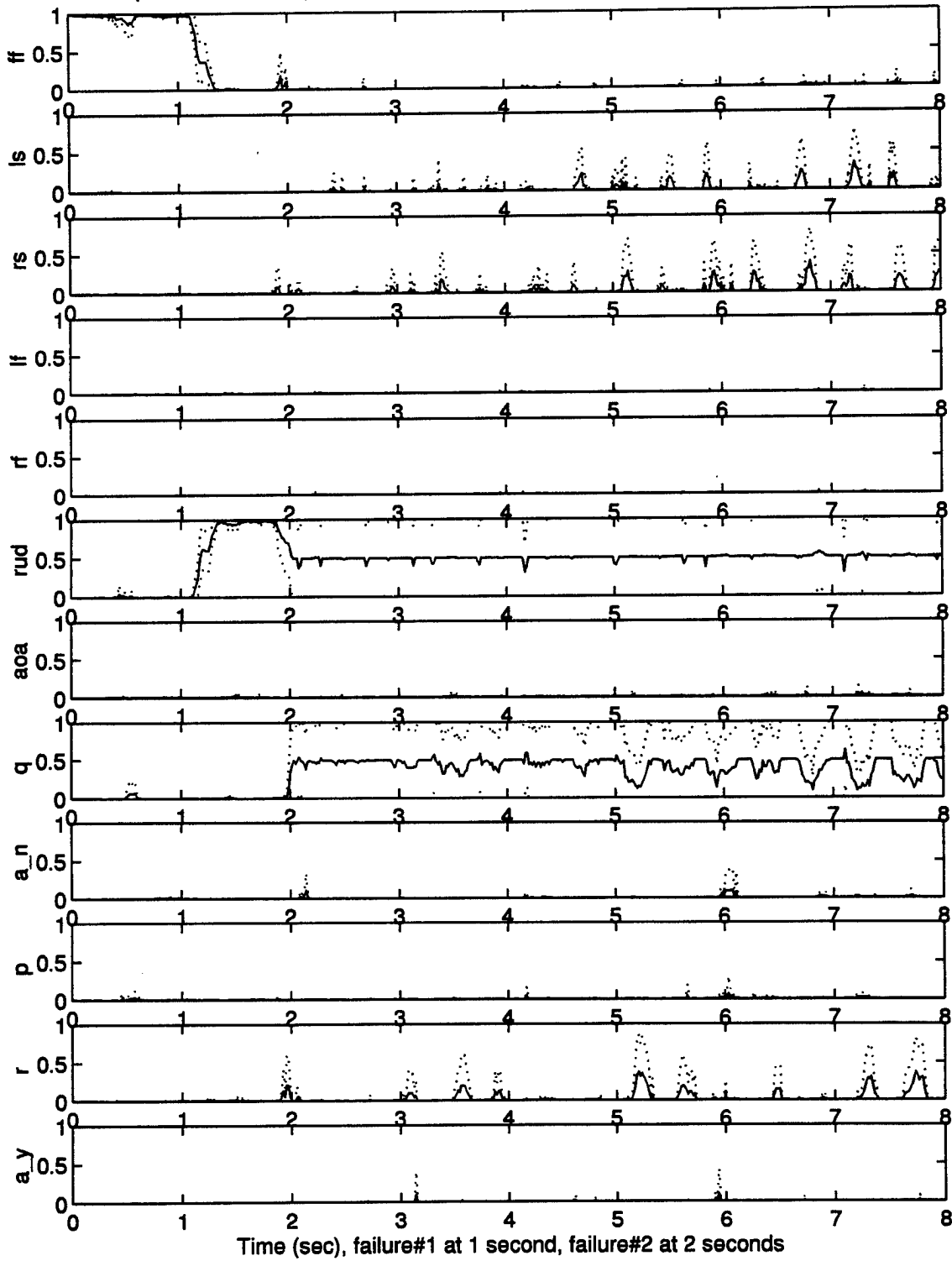
Mean (+/- One Std Dev) Dual-fail Probabilities of fail255.254 with reconfiguration: 10 runs



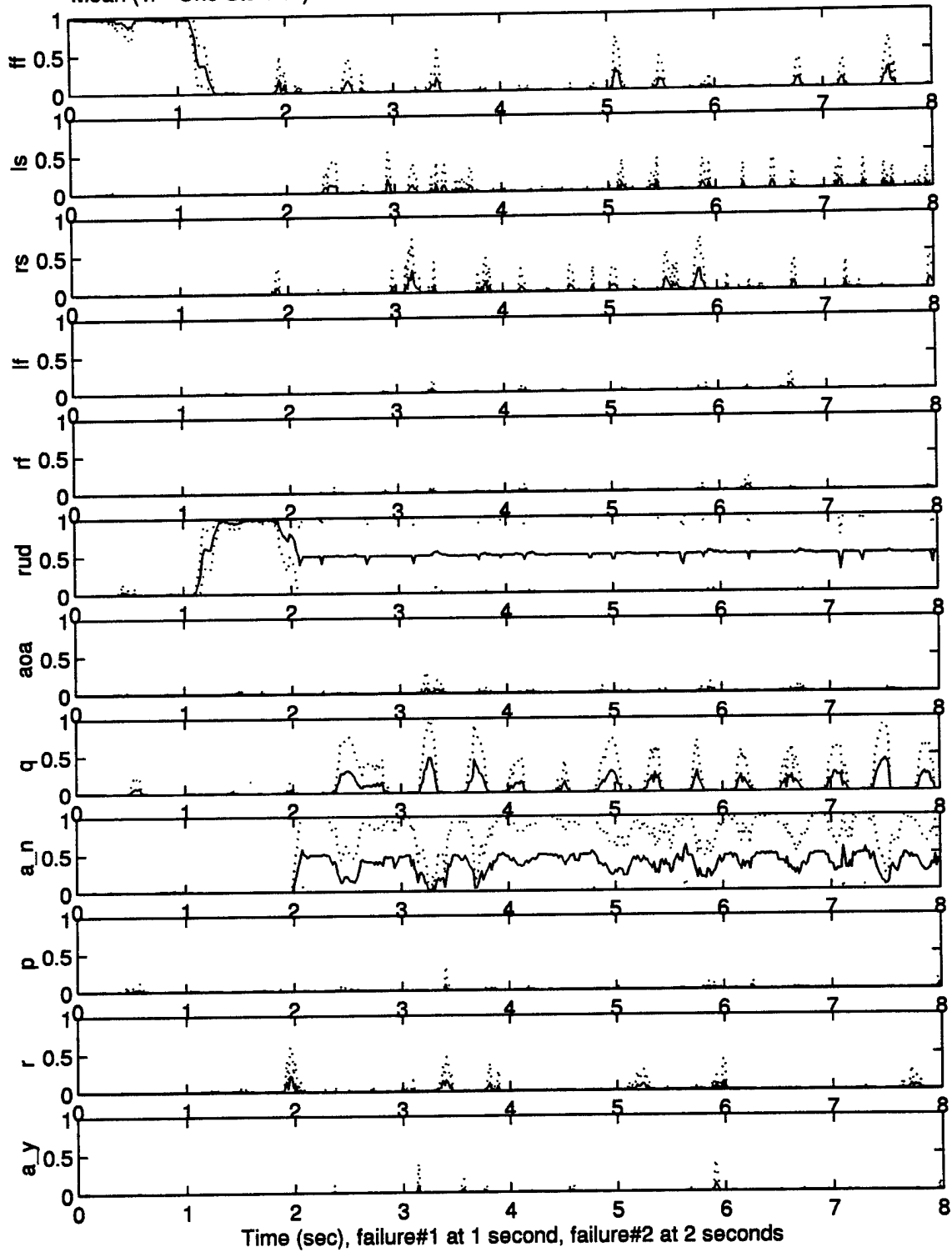
Mean (+/- One Std Dev) Dual-fail Probabilities of fail255.06 with reconfiguration: 10 runs



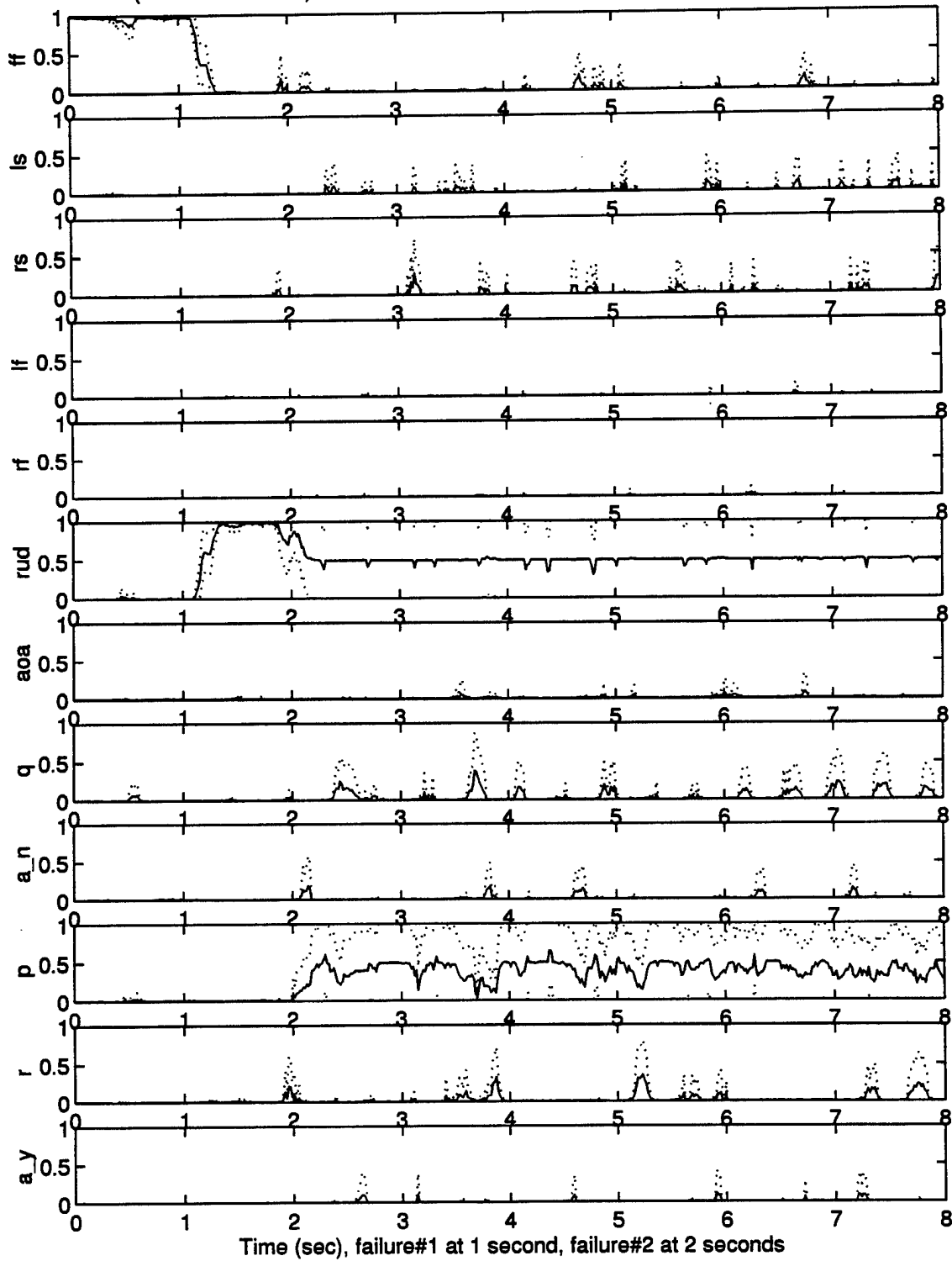
Mean (+/- One Std Dev) Dual-fail Probabilities of fail255.07 with reconfiguration: 10 runs



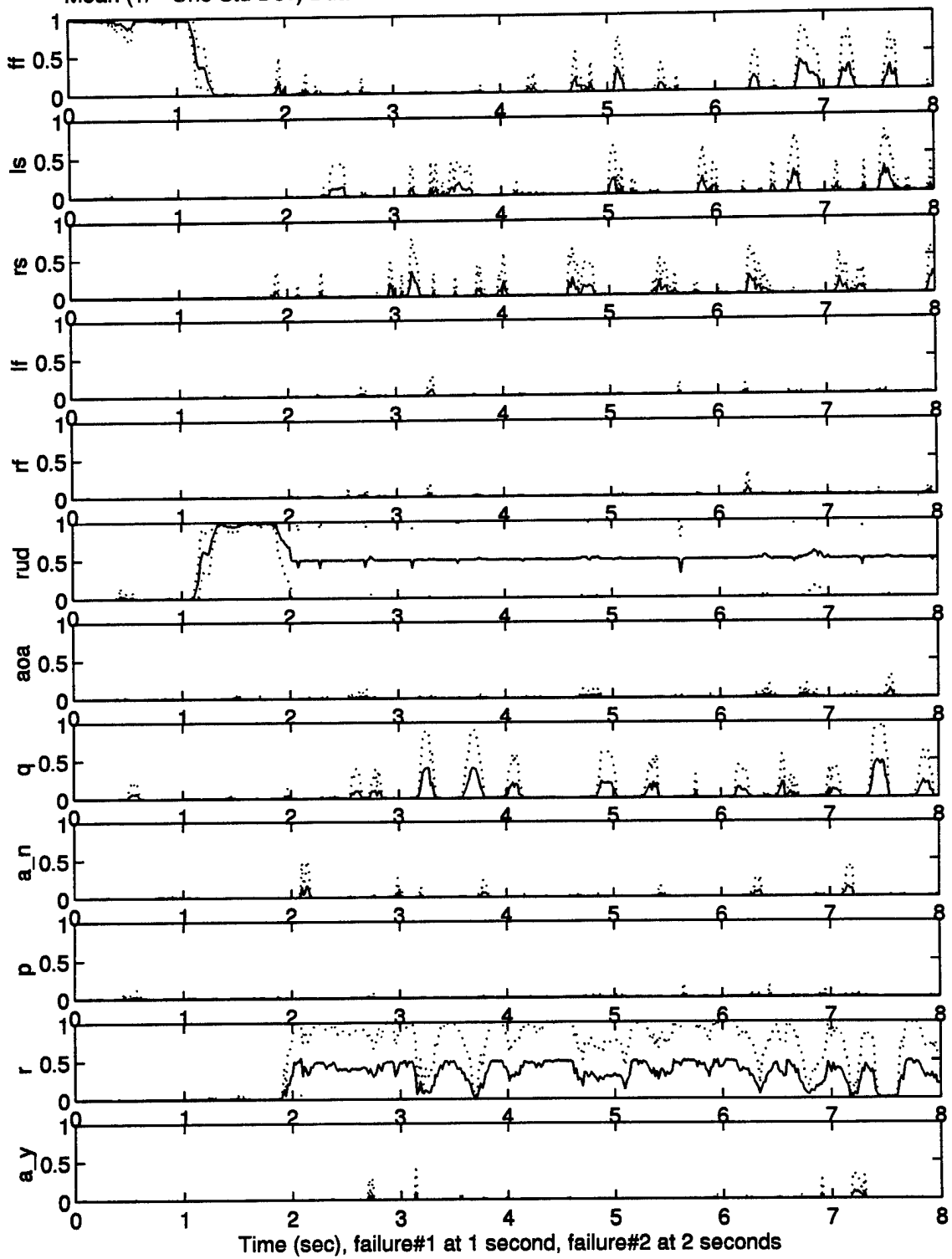
Mean (+/- One Std Dev) Dual-fail Probabilities of fail255.08 with reconfiguration: 10 runs



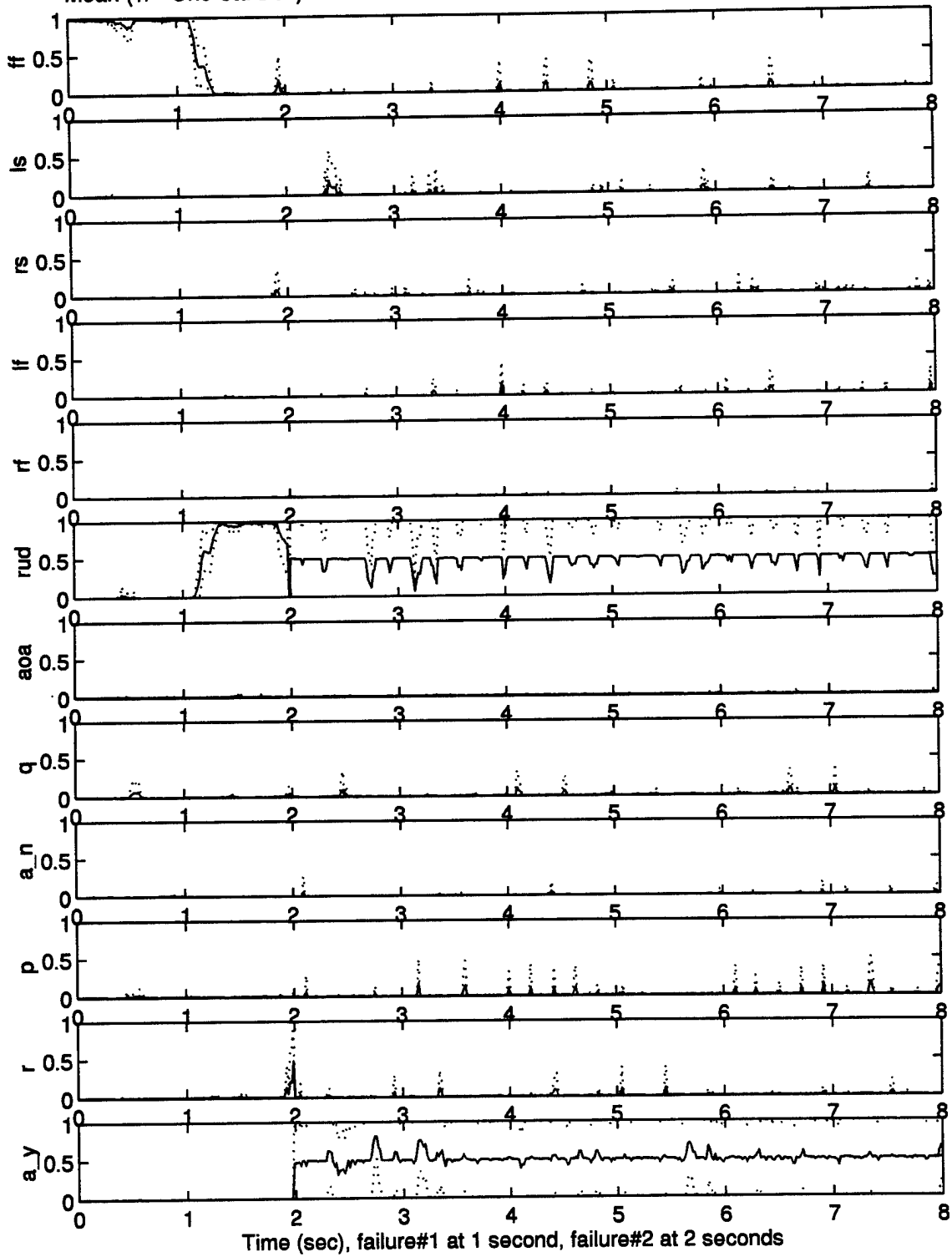
Mean (+/- One Std Dev) Dual-fail Probabilities of fail255.09 with reconfiguration: 10 runs



Mean (+/- One Std Dev) Dual-fail Probabilities of fail255.010 with reconfiguration: 10 runs



Mean (+/- One Std Dev) Dual-fail Probabilities of fail255.011 with reconfiguration: 10 runs



*Appendix D.3: Dual, 50% Actuator ($\epsilon = .5$) and 50%-Actuator / Total -Sensor Impairments,
Control Redistribution 'ON', Dither 'ON', No Maneuvers*

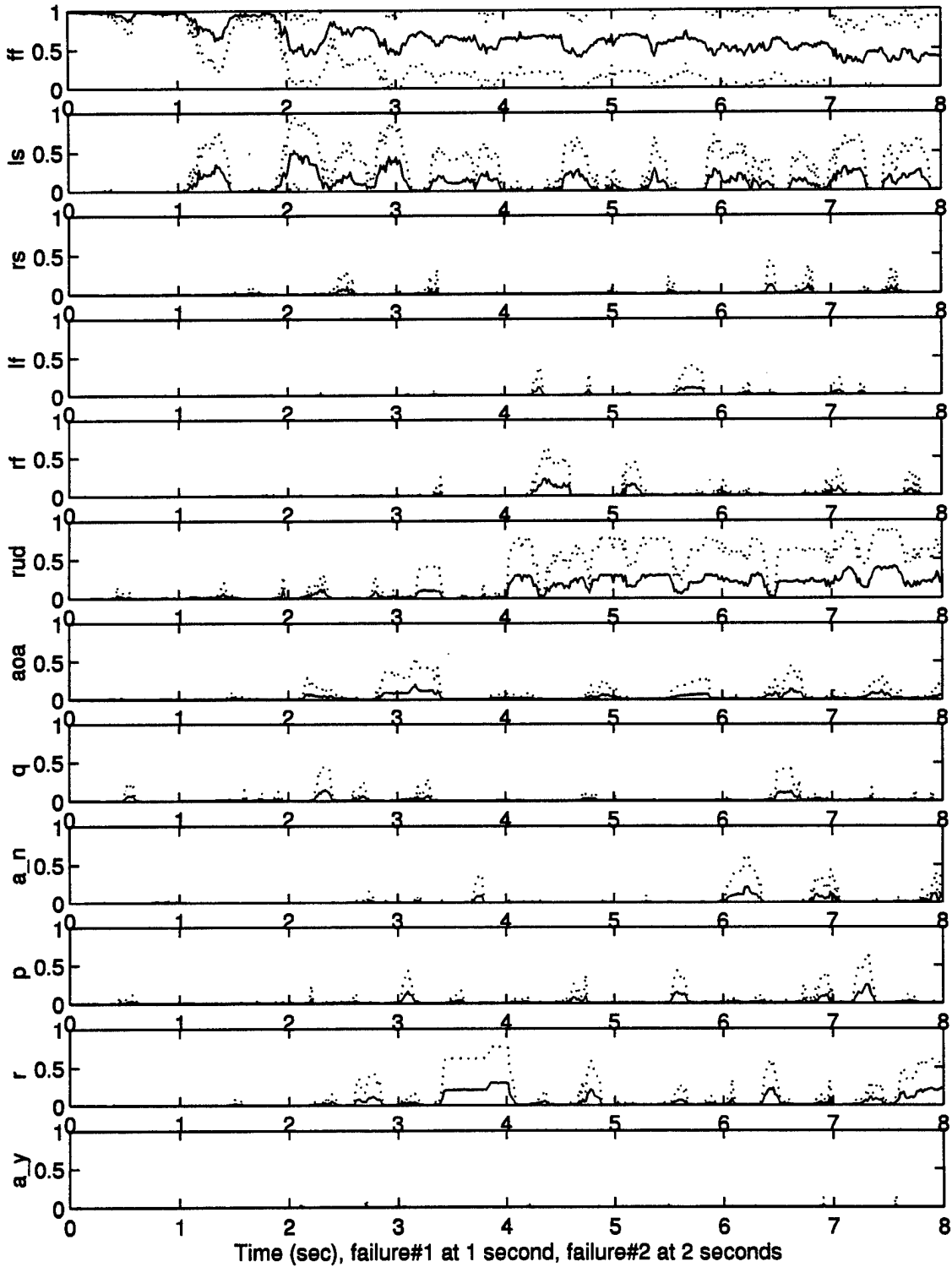
This appendix contains the individual probability plots for “50% actuator / 50% actuator” and “50% actuator / total sensor” dual impairment scenarios, *with* Control Reconfiguration (Redistribution) and with control dithering (Section 4.13.3). The first impairment is inserted at 1 second, followed by the second impairment at 2 seconds, and in all cases, there is no aircraft maneuvering. Table D.3 on the following page lists the impairment cases, by case number, which are to be found in this appendix. The leftmost column of Table D.3 represents the first impairment occurring at 1 second, while the top row represents the second impairment occurring at 2 seconds. The table entries list the failure codes found in the plot titles for the failure case represented by the table row and column. **Bold** entries correspond to cases of no second impairment. As an example, the entry for a 50% left stabilator (LS) impairment at 1 second, followed by a 50% right flaperon (RF) impairment at 2 seconds is found in entry ‘(LS, RF)’ in the table, and the corresponding failure case is ‘fail501.504’. The convention was to use effectiveness, ϵ , in naming the plots, and hence ‘fail501.504’ corresponds to 50% actuator *effectiveness*, or a 50% actuator impairment. The probability plot will contain this code (‘fail501.504’) in the plot title. In fact, for this specific case, the plot title is: “Mean (+ / - One Std Dev) Dual-fail Probabilities of fail501.504 with reconfiguration: 10 runs”. The reader is reminded that, after the switch to the Level ‘1’ filter bank, the meanings of the probability traces in the plots (except for the fully functional trace, which retains the same meaning) change to that of the first impairment *plus* the second impairment.

Second Impairment

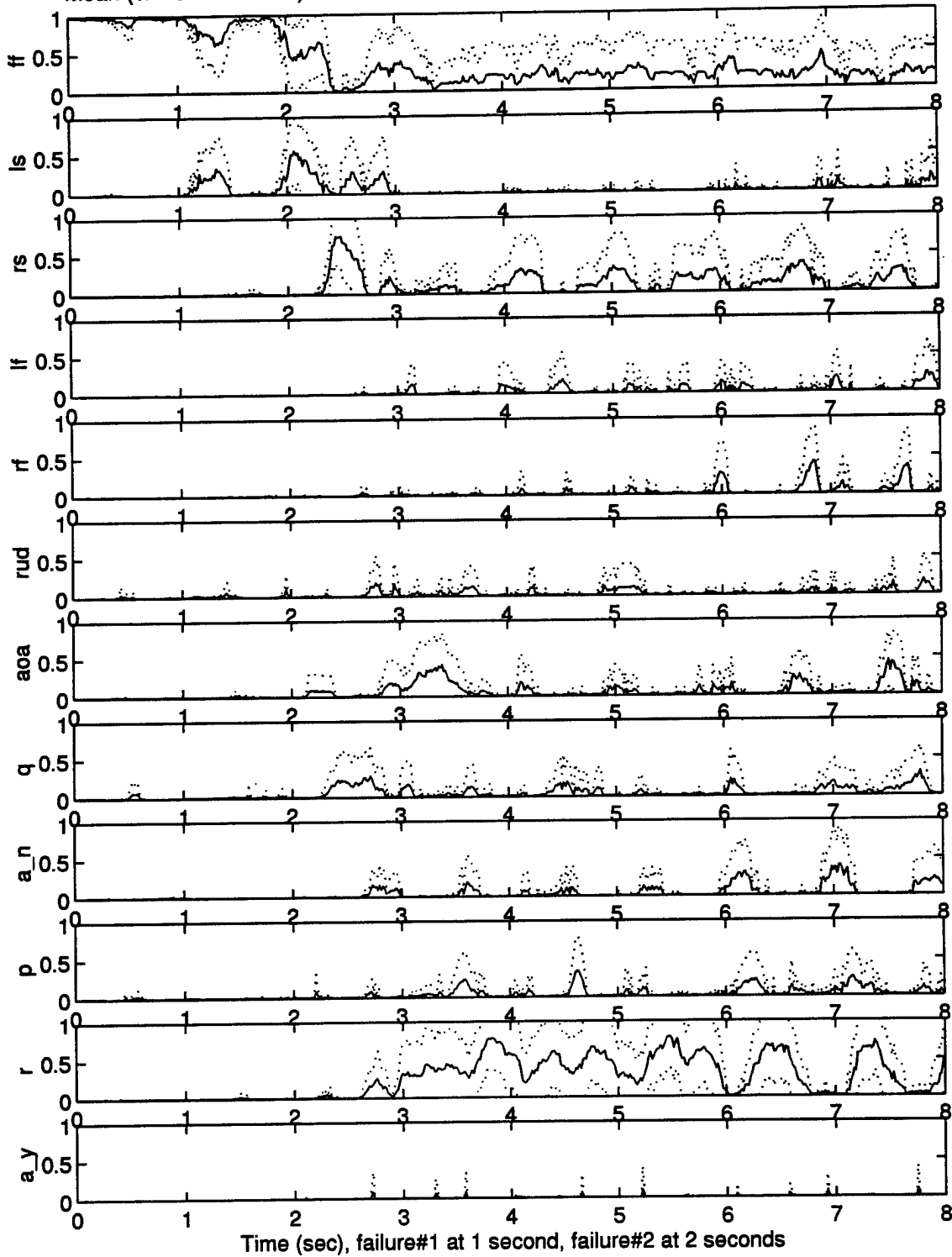
	LS (50%)	RS (50%)	LF (50%)	RF (50%)	RUD (50%)	AOA (100%)	Q (100%)	A_n (100%)	P (100%)	R (100%)	A_y (100%)
LS (50%)	fail501.500	fail501.502	fail501.503	fail501.504	fail501.505	fail501.06	fail501.07	fail501.08	fail501.09	fail501.010	fail501.011
RS (50%)	fail502.501	fail502.500	fail502.503	fail502.504	fail502.505	fail502.06	fail502.07	fail502.08	fail502.09	fail502.010	fail502.011
LF (50%)	fail503.501	fail503.502	fail503.500	fail503.504	fail503.505	fail503.06	fail503.07	fail503.08	fail503.09	fail503.010	fail503.011
RF (50%)	fail504.501	fail504.502	fail504.503	fail504.500	fail504.505	fail504.06	fail504.07	fail504.08	fail504.09	fail504.010	fail504.011
RUD (50%)	fail505.501	fail505.502	fail505.503	fail505.504	fail505.500	fail505.06	fail505.07	fail505.08	fail505.09	fail505.010	fail505.011

Table D.3 A Listing of All Probability Plots Found in Appendix D.3 by Failure Case

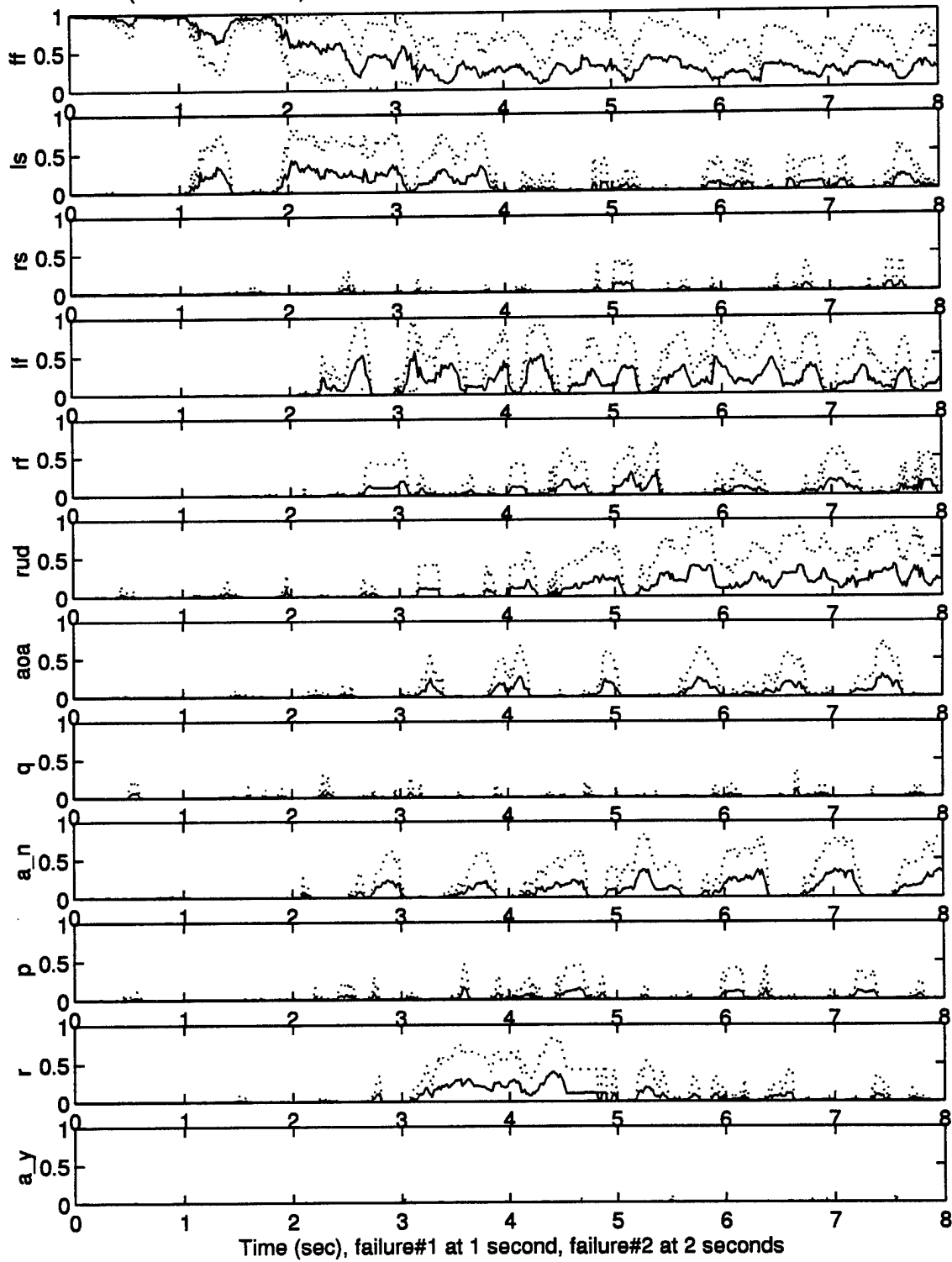
Mean (+/- One Std Dev) Dual-fail Probabilities of fail501.500 with reconfiguration: 10 runs



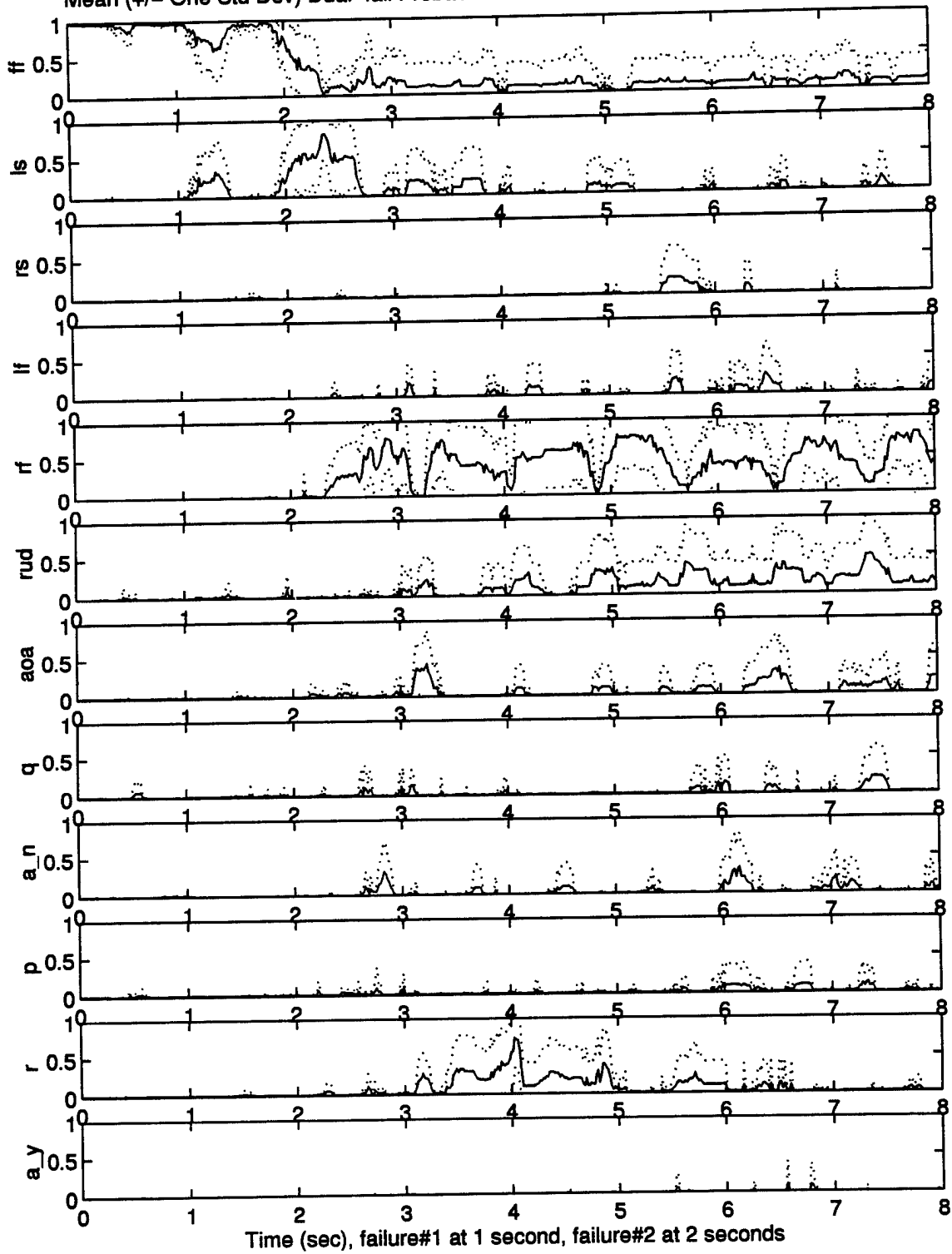
Mean (+/- One Std Dev) Dual-fail Probabilities of fail501.502 with reconfiguration: 10 runs



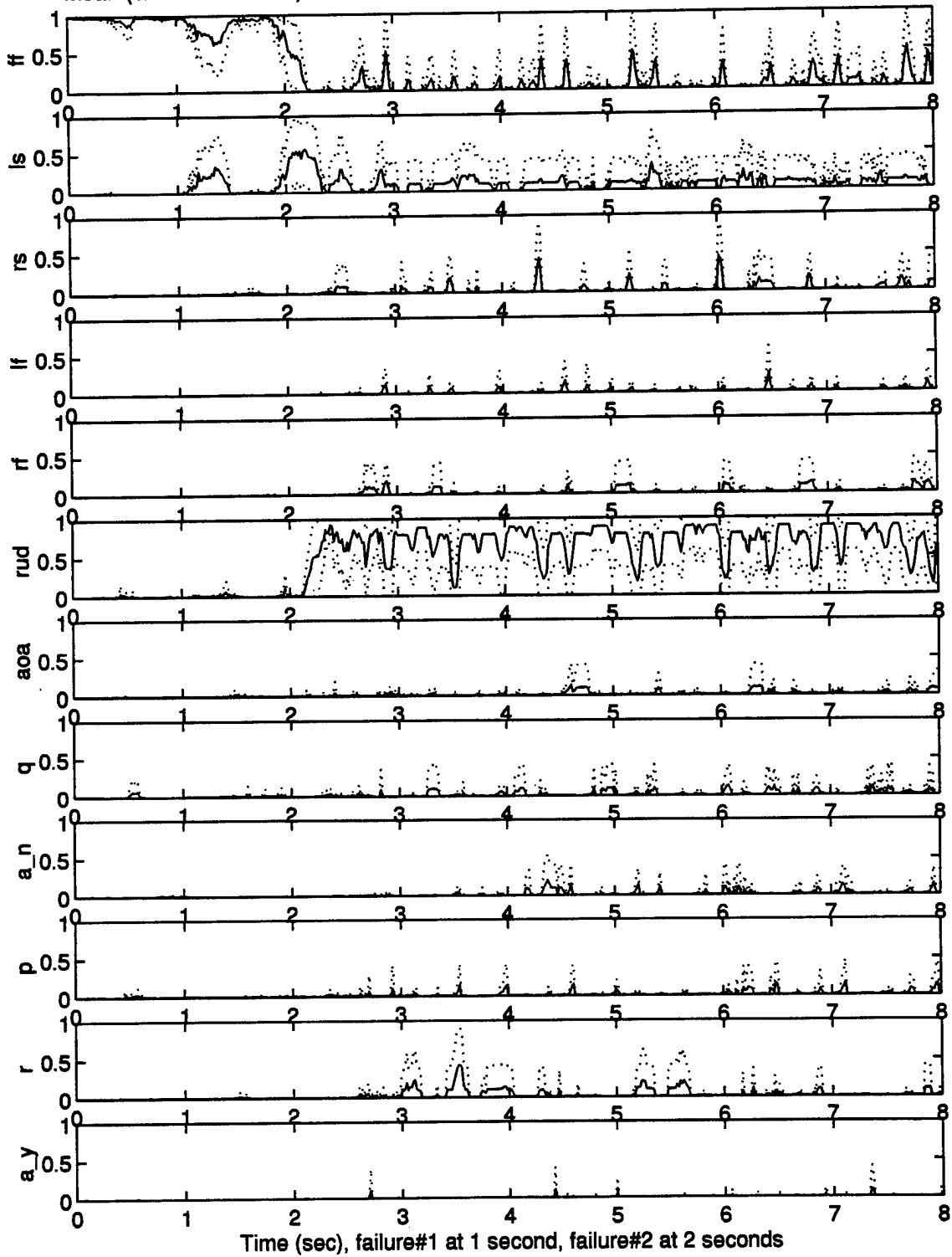
Mean (+/- One Std Dev) Dual-fail Probabilities of fail501.503 with reconfiguration: 10 runs



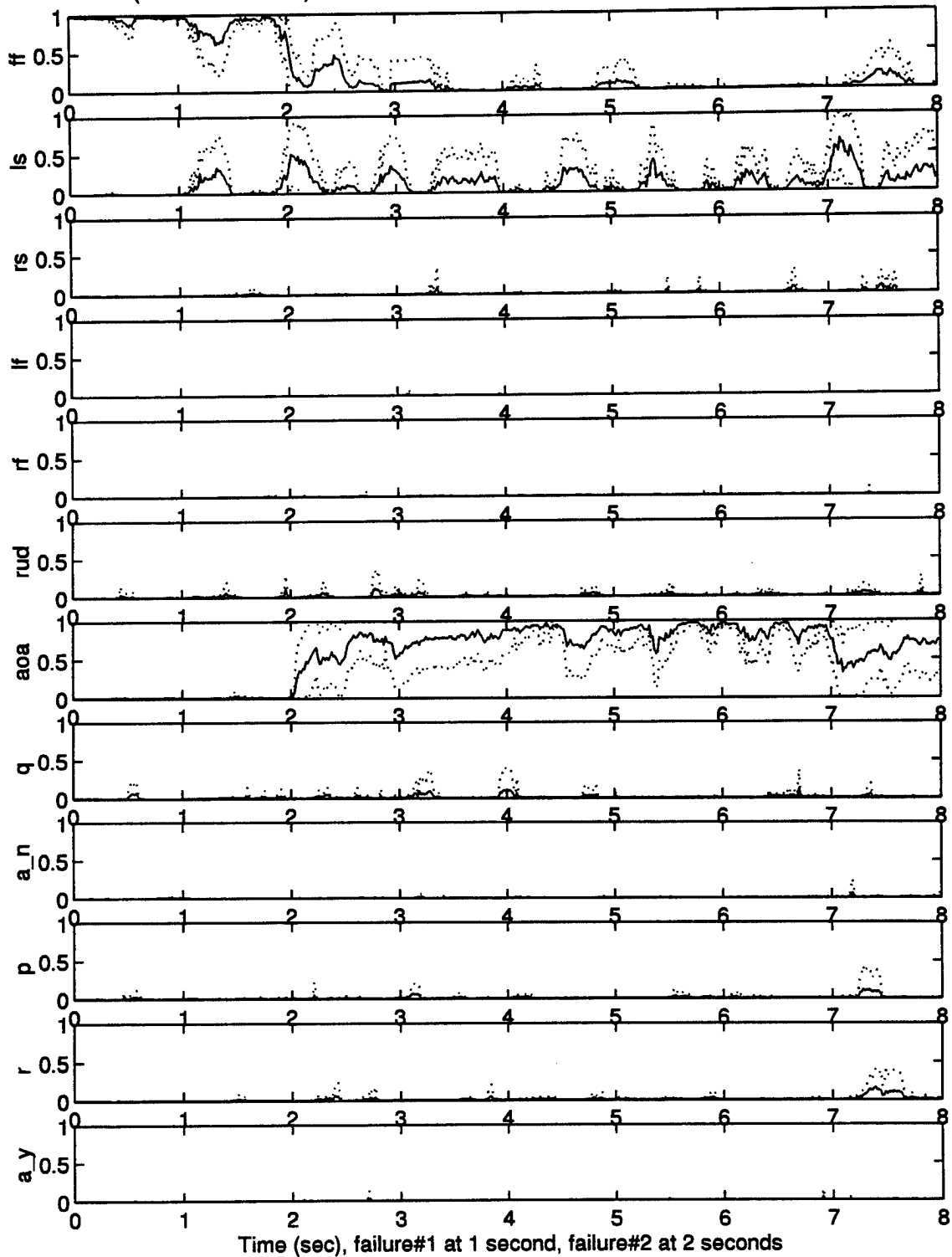
Mean (+/- One Std Dev) Dual-fail Probabilities of fail501.504 with reconfiguration: 10 runs



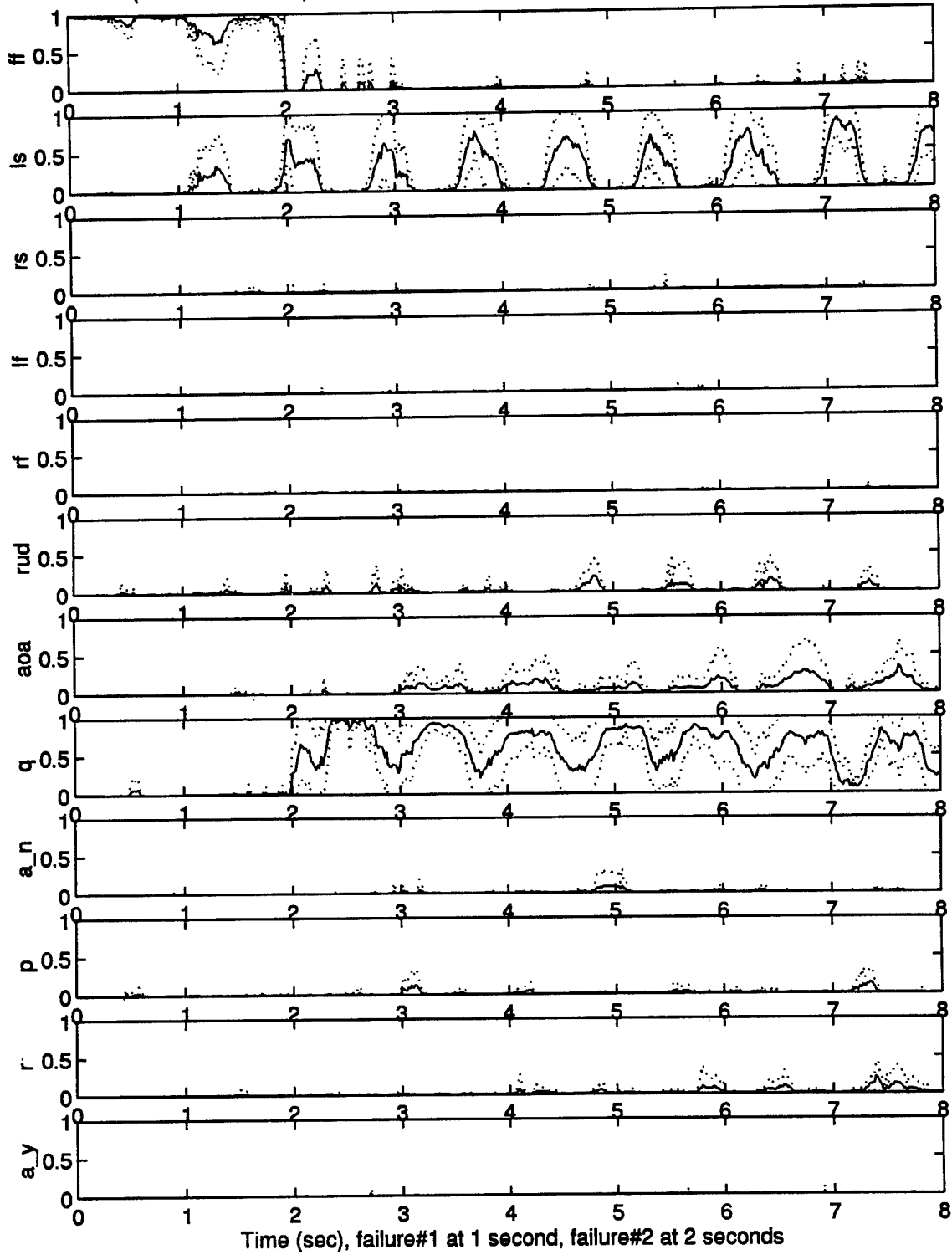
Mean (+/- One Std Dev) Dual-fail Probabilities of fail501.505 with reconfiguration: 10 runs



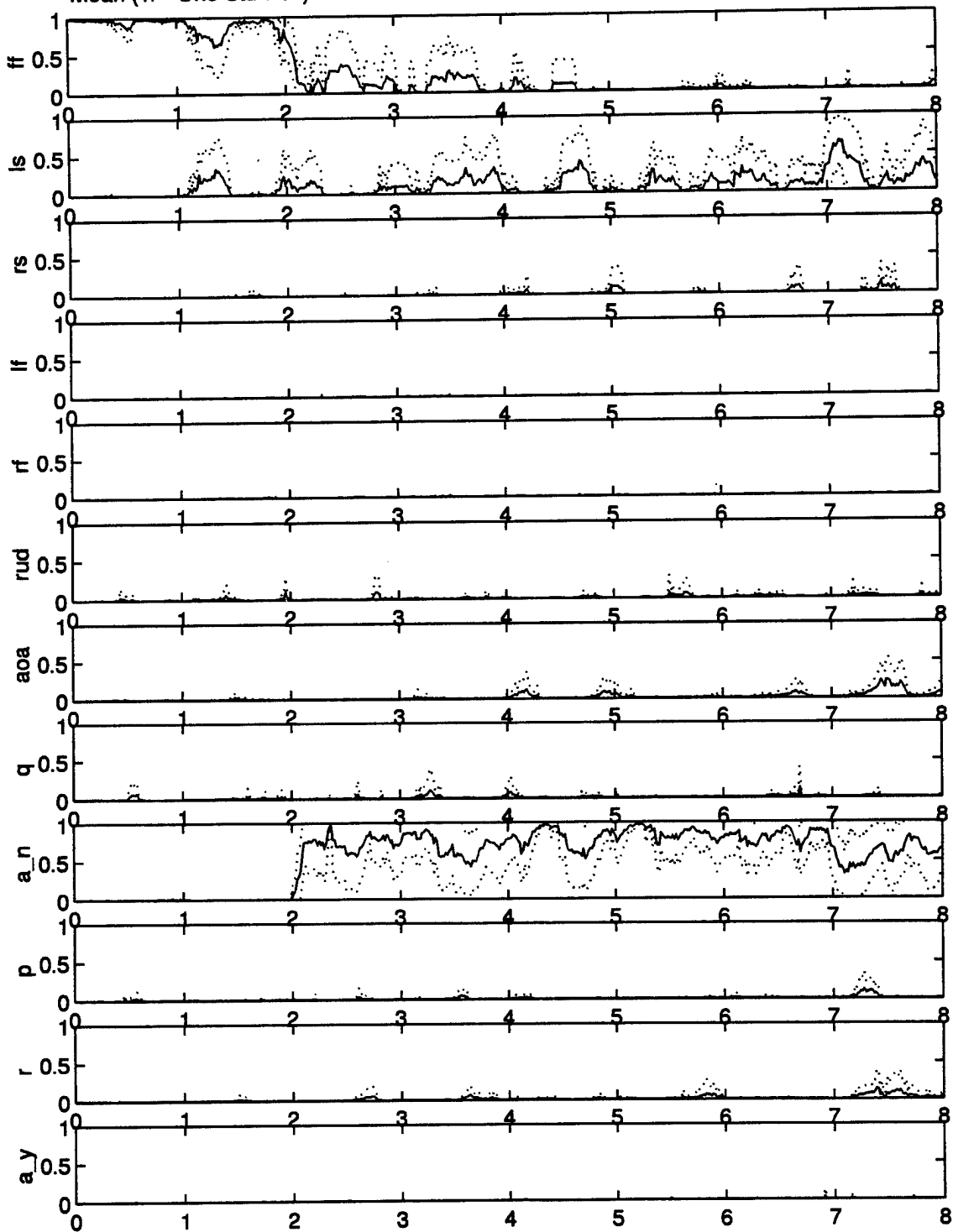
Mean (+/- One Std Dev) Dual-fail Probabilities of fail501.06 with reconfiguration: 10 runs



Mean (+/- One Std Dev) Dual-fail Probabilities of fail501.07 with reconfiguration: 10 runs

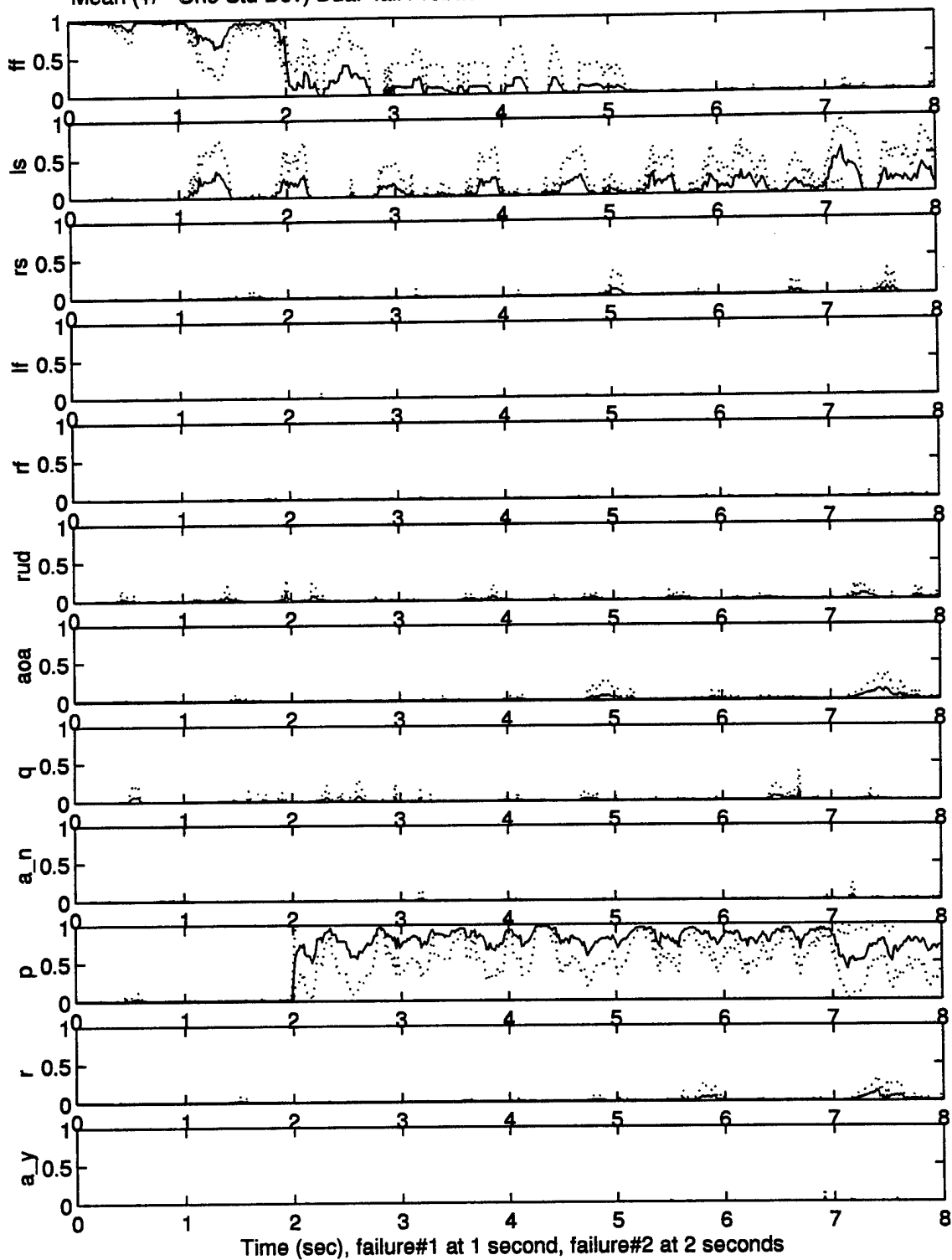


Mean (+/- One Std Dev) Dual-fail Probabilities of fail501.08 with reconfiguration: 10 runs

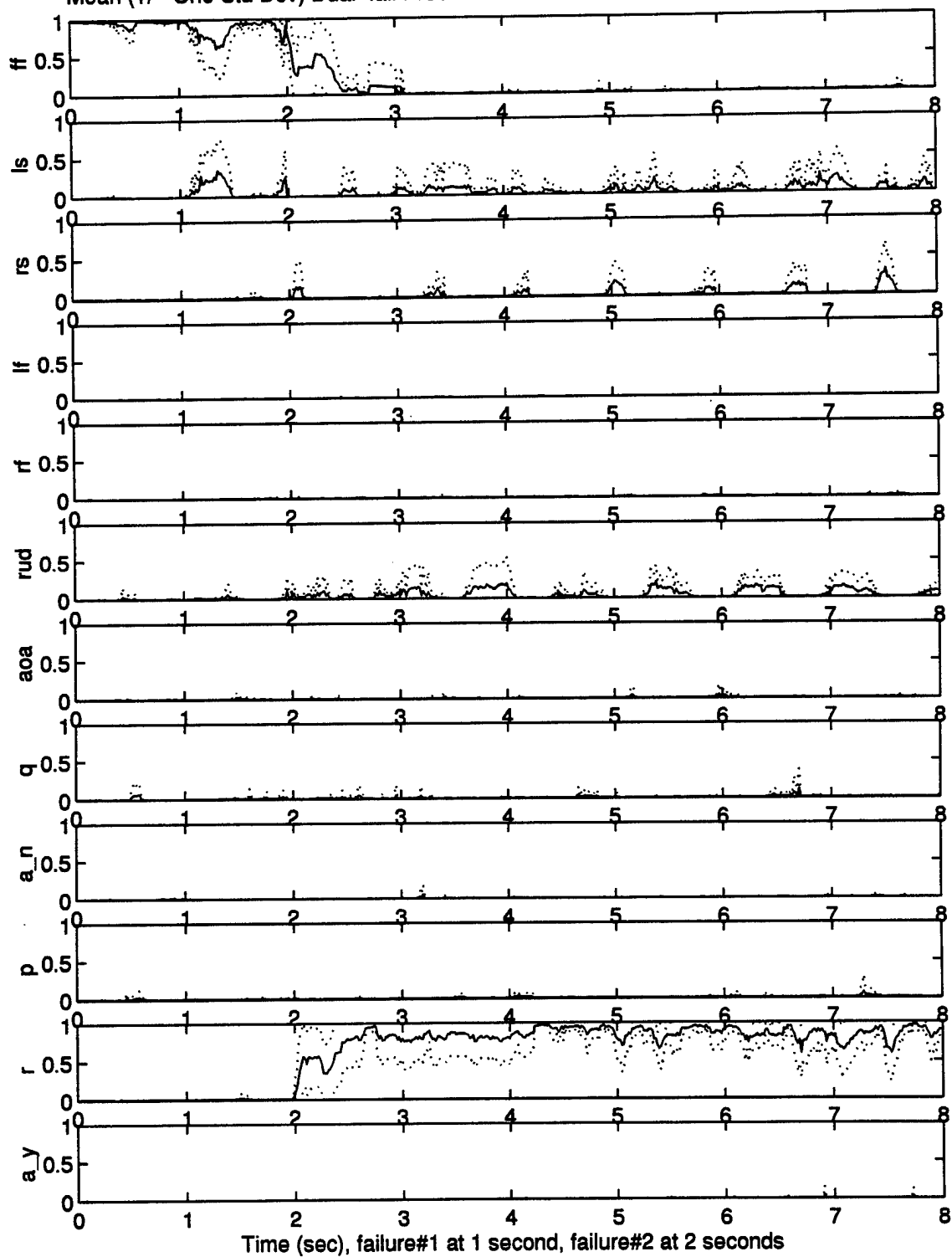


Time (sec), failure#1 at 1 second, failure#2 at 2 seconds

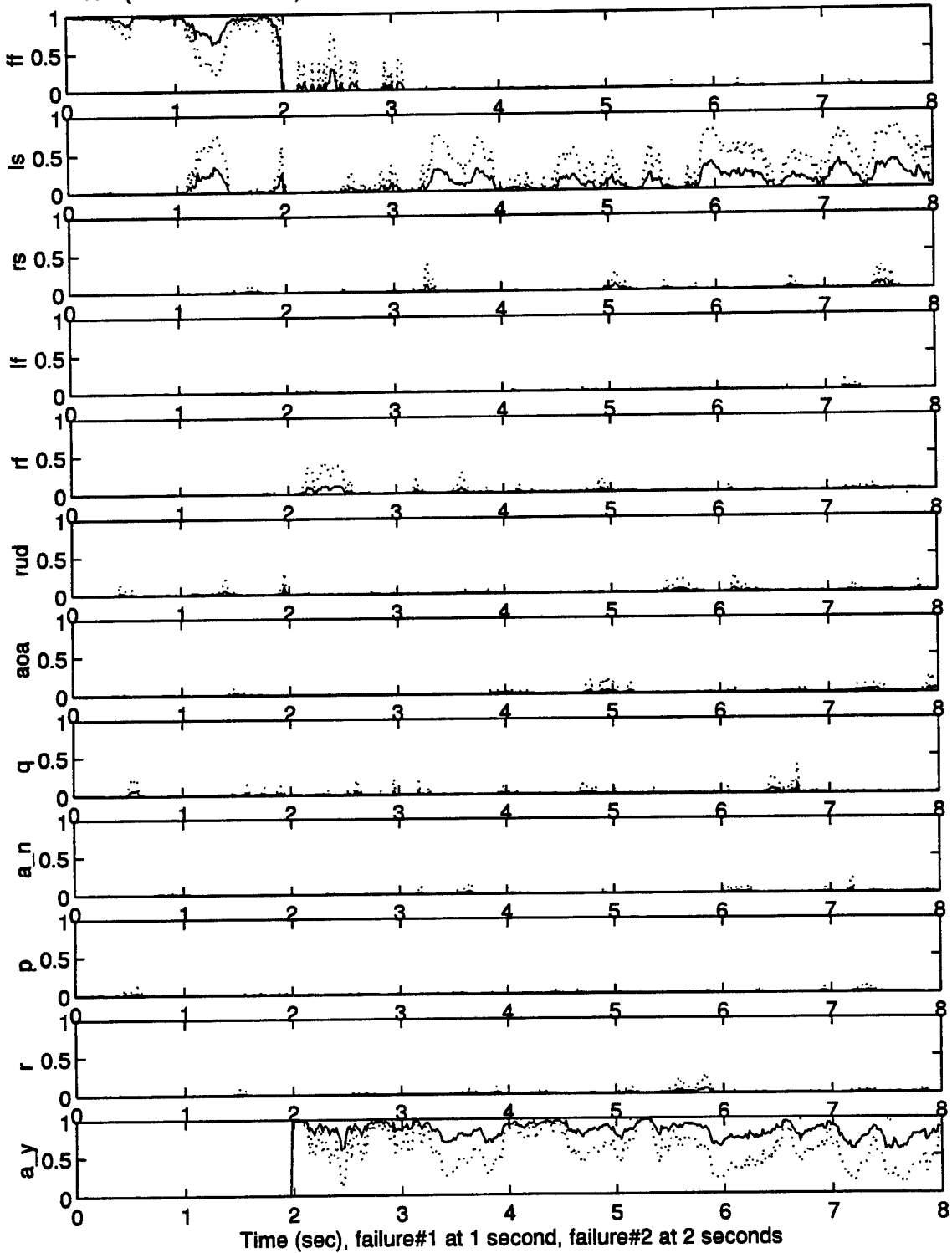
Mean (+/- One Std Dev) Dual-fail Probabilities of fail501.09 with reconfiguration: 10 runs



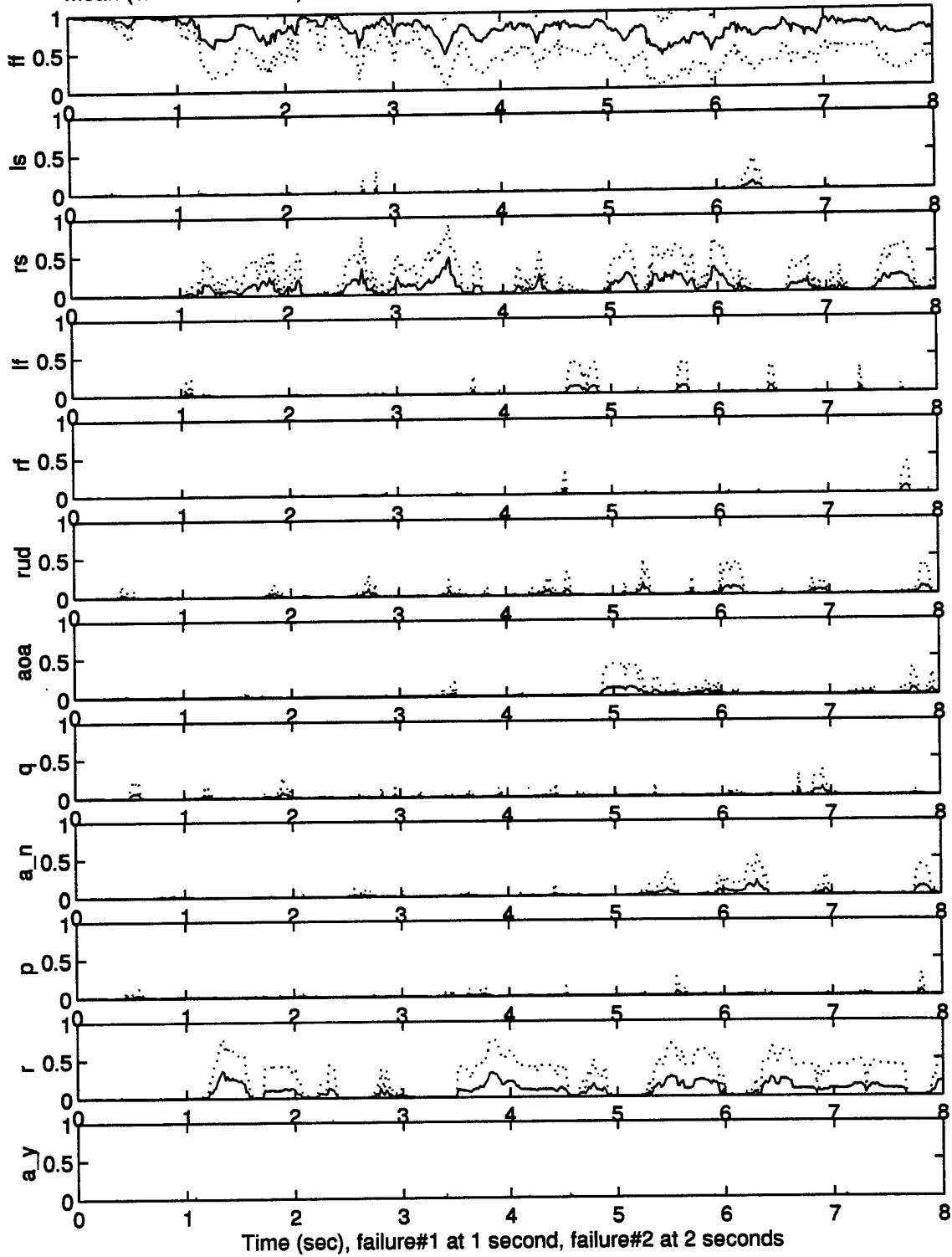
Mean (+/- One Std Dev) Dual-fail Probabilities of fail501.010 with reconfiguration: 10 runs



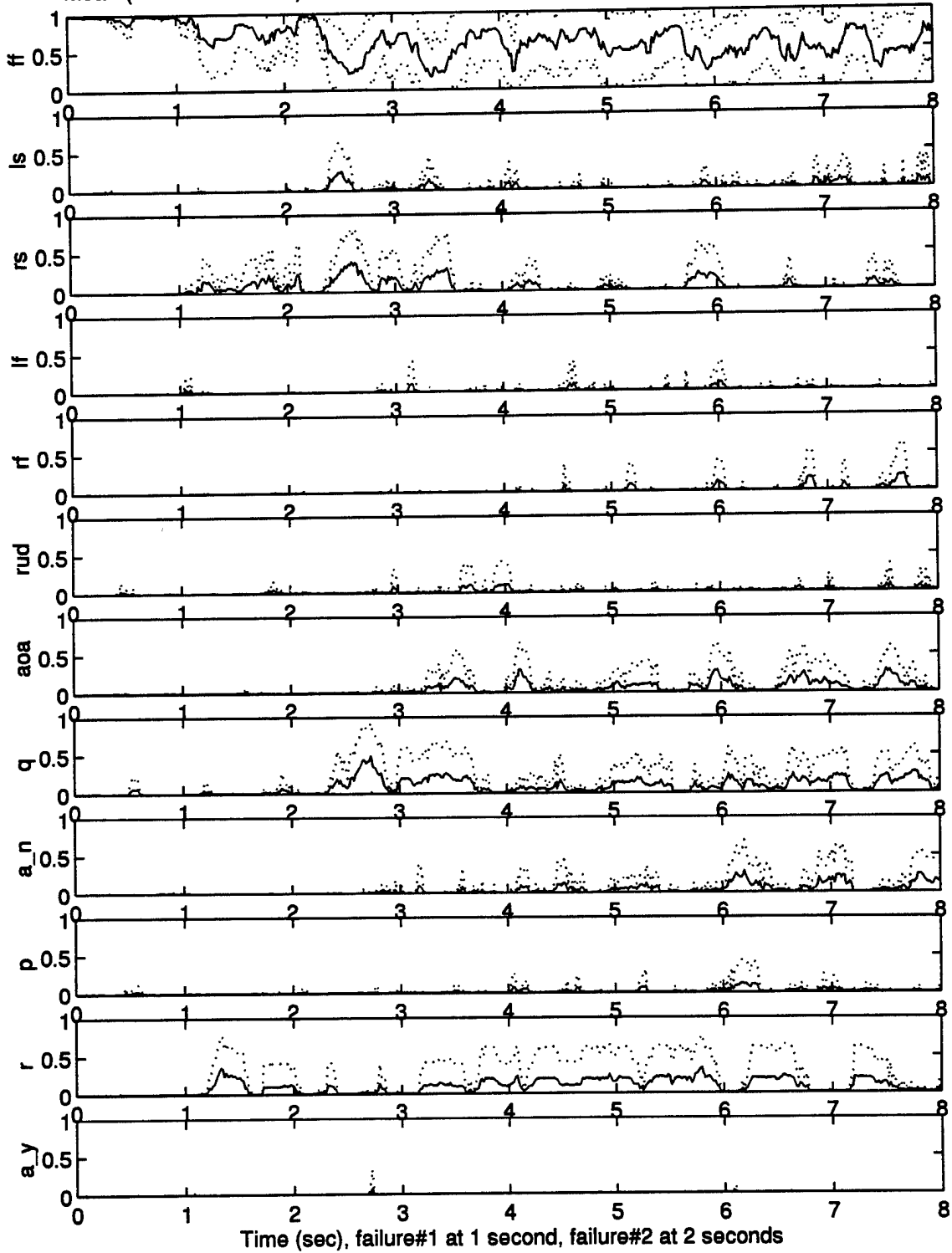
Mean (+/- One Std Dev) Dual-fail Probabilities of fail501.011 with reconfiguration: 10 runs



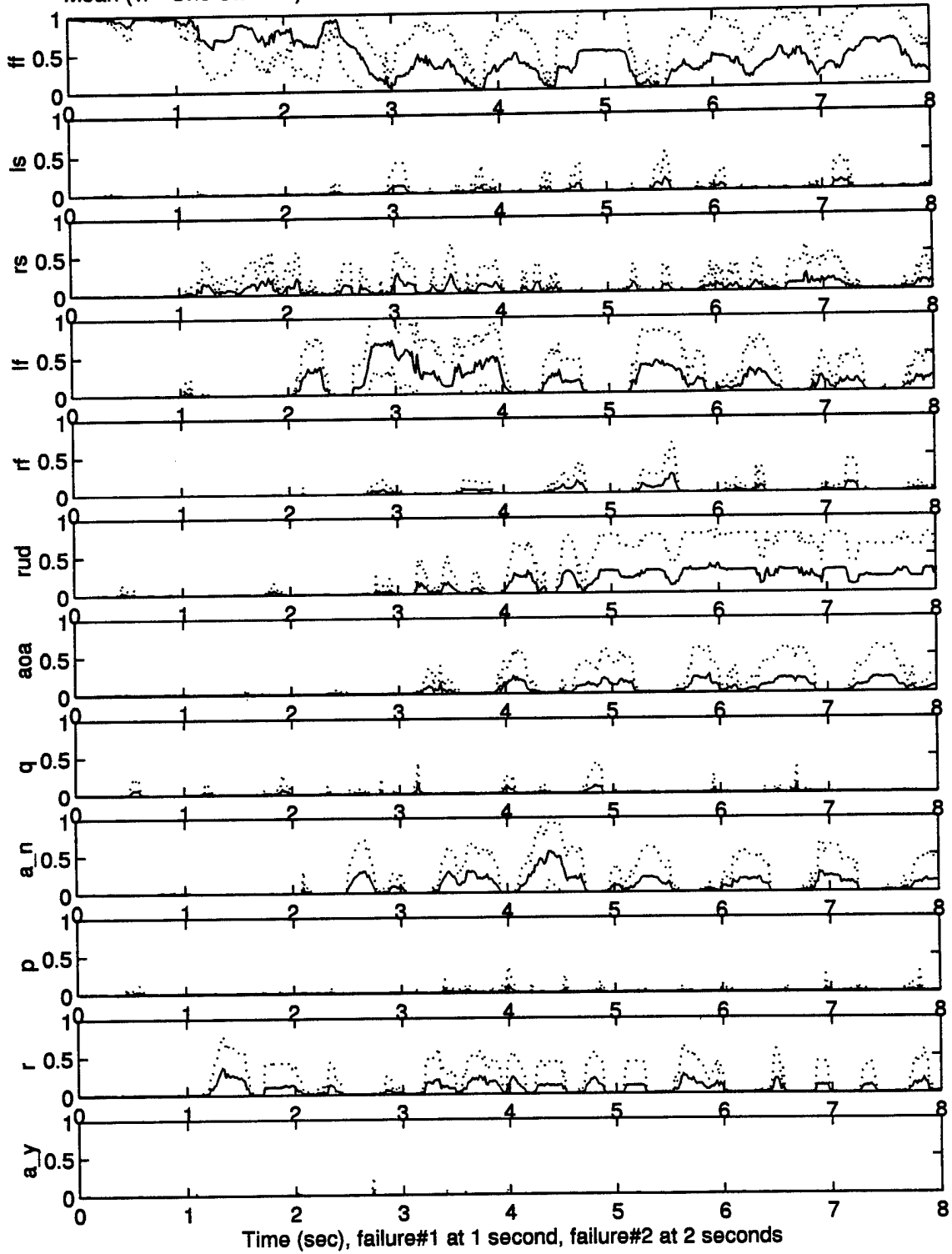
Mean (+/- One Std Dev) Dual-fail Probabilities of fail502.500 with reconfiguration: 10 runs



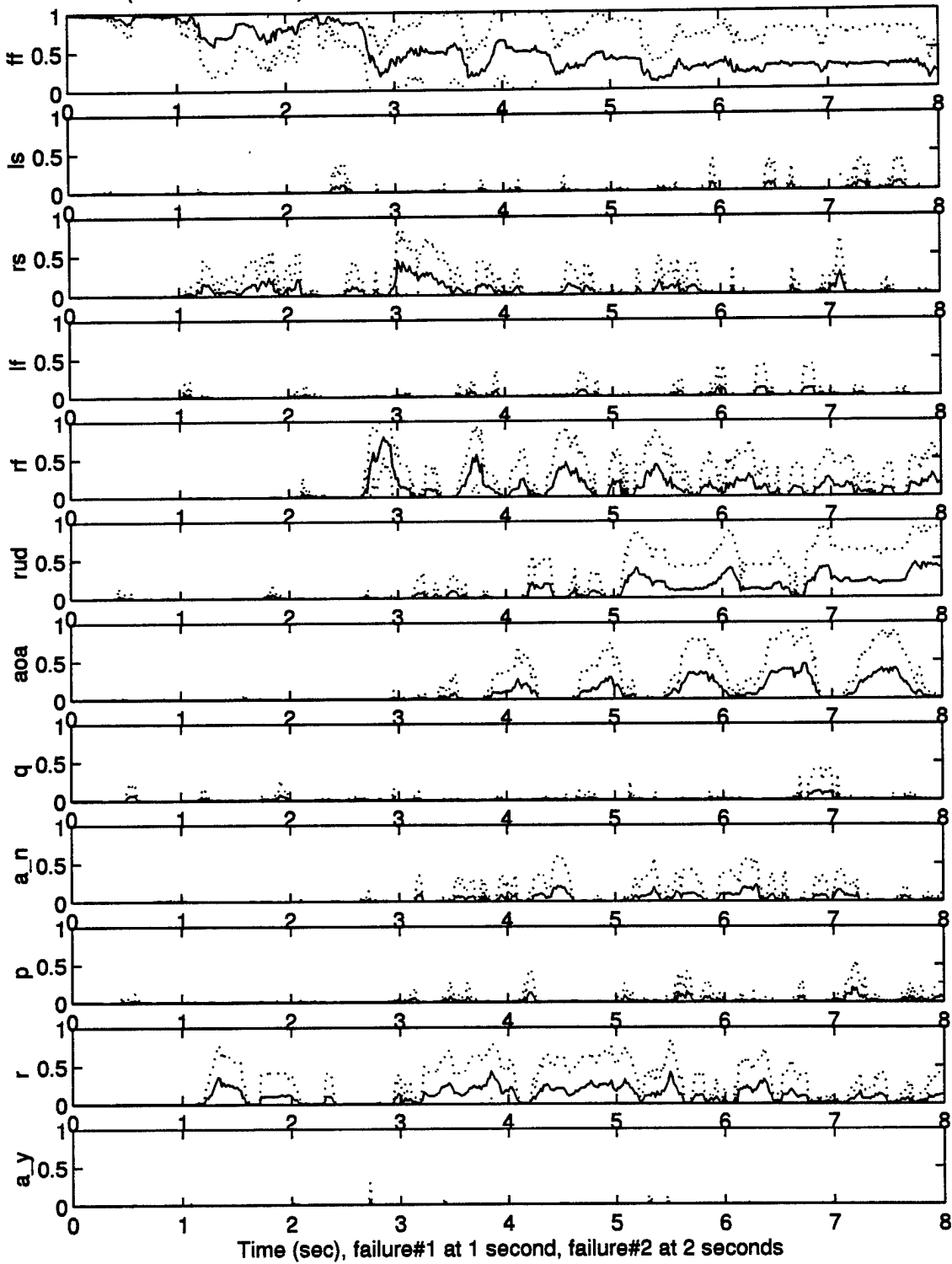
Mean (+/- One Std Dev) Dual-fail Probabilities of fail502.501 with reconfiguration: 10 runs



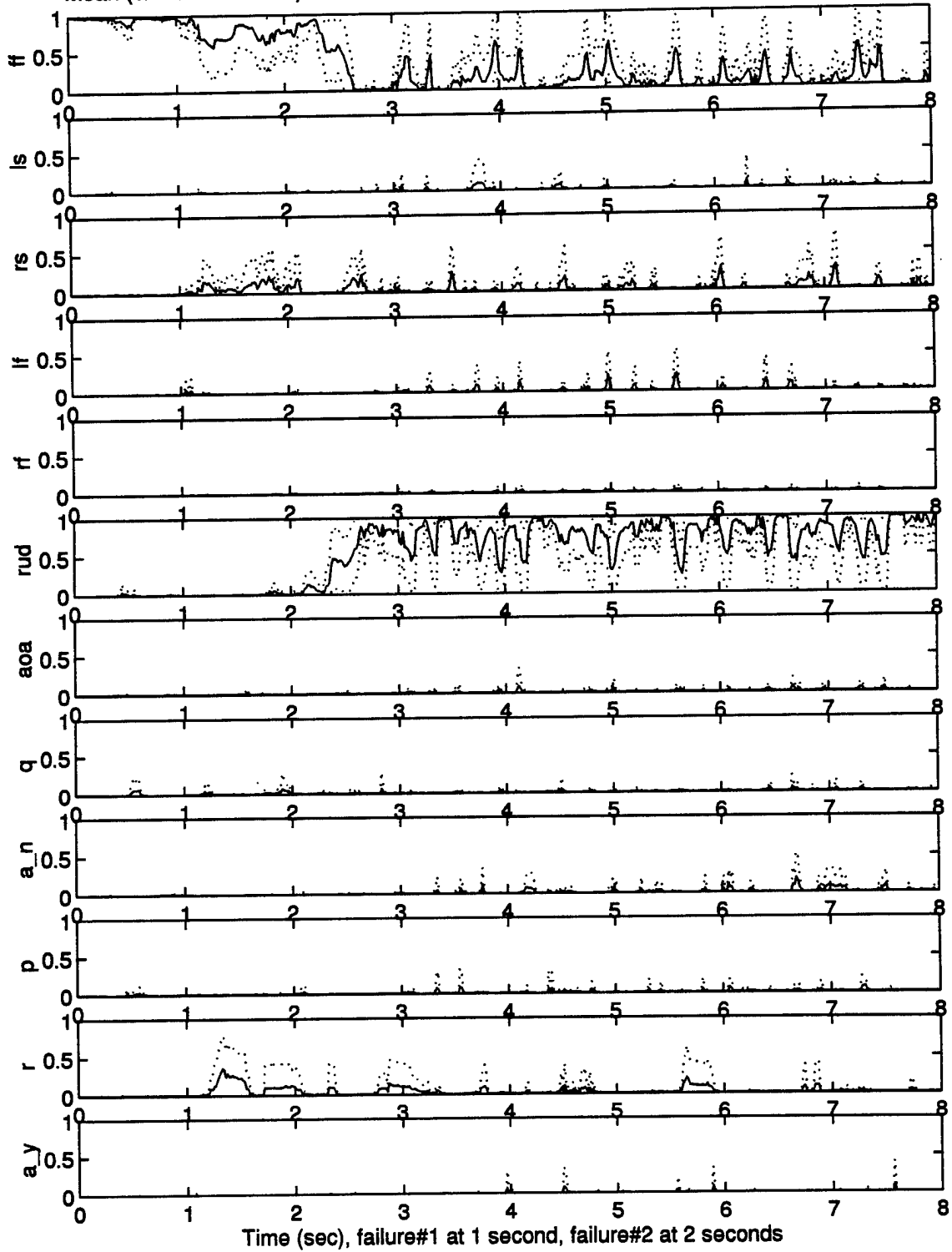
Mean (+/- One Std Dev) Dual-fail Probabilities of fail502.503 with reconfiguration: 10 runs



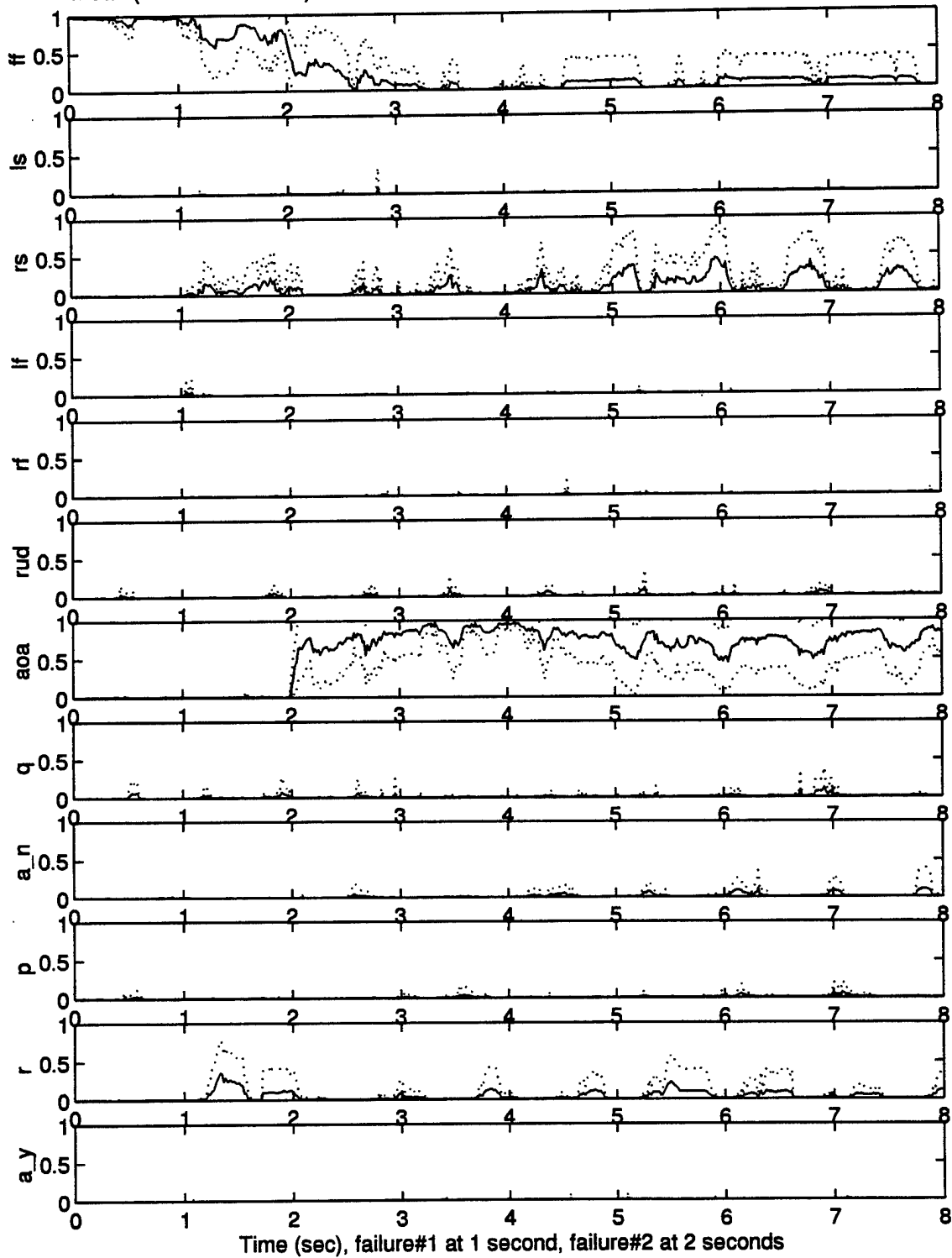
Mean (+/- One Std Dev) Dual-fail Probabilities of fail502.504 with reconfiguration: 10 runs



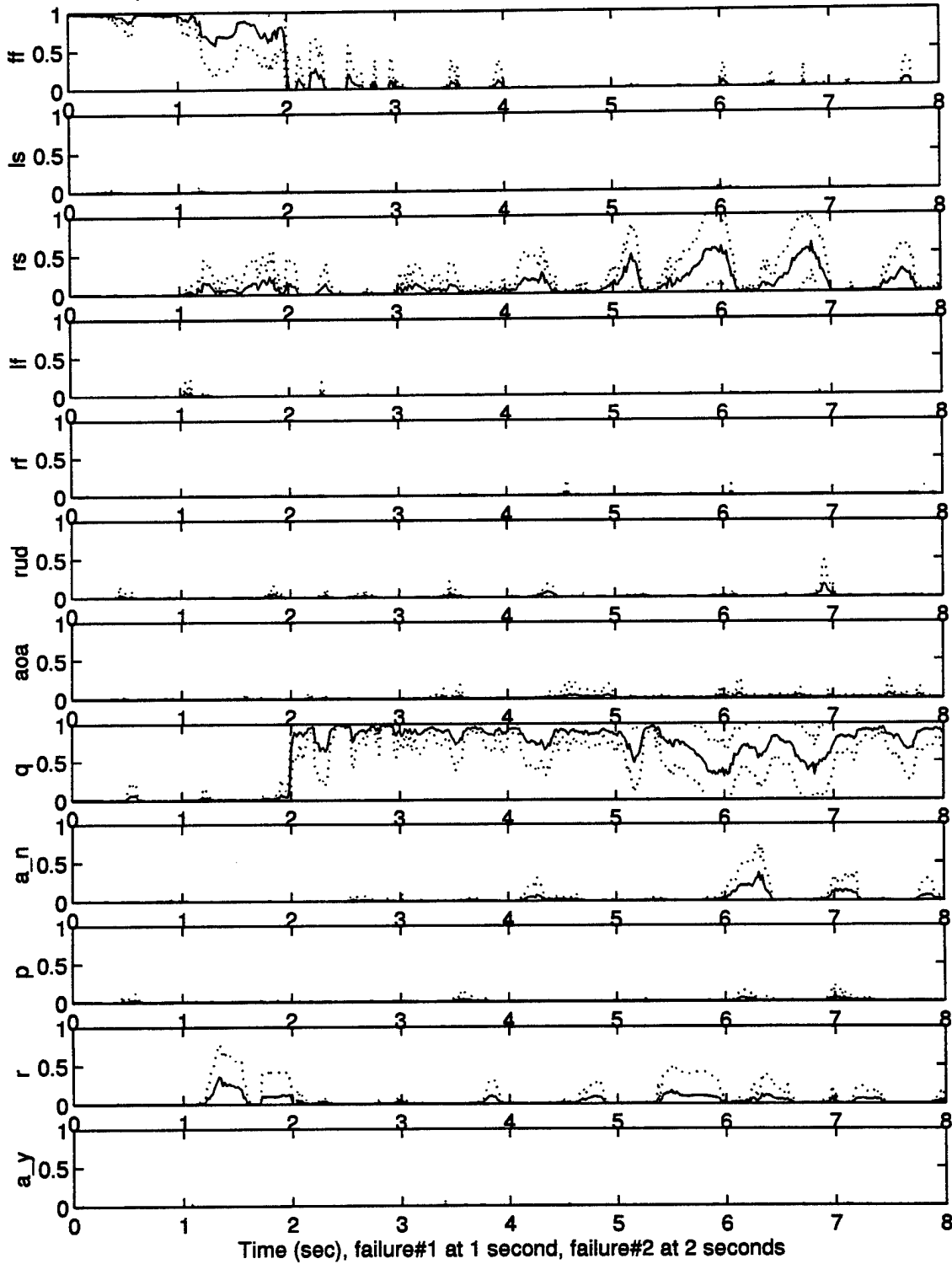
Mean (+/- One Std Dev) Dual-fail Probabilities of fail502.505 with reconfiguration: 10 runs



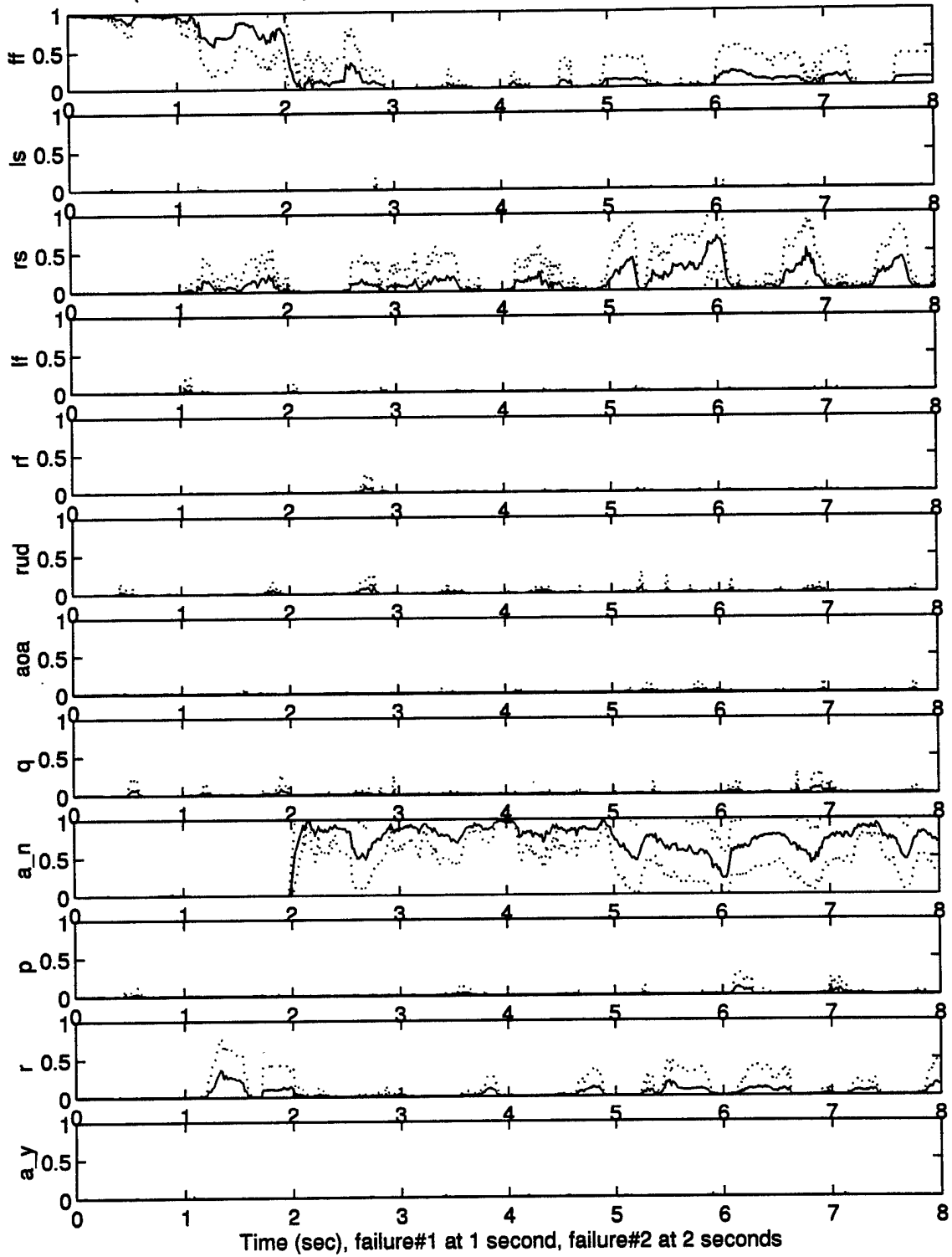
Mean (+/- One Std Dev) Dual-fail Probabilities of fail502.06 with reconfiguration: 10 runs



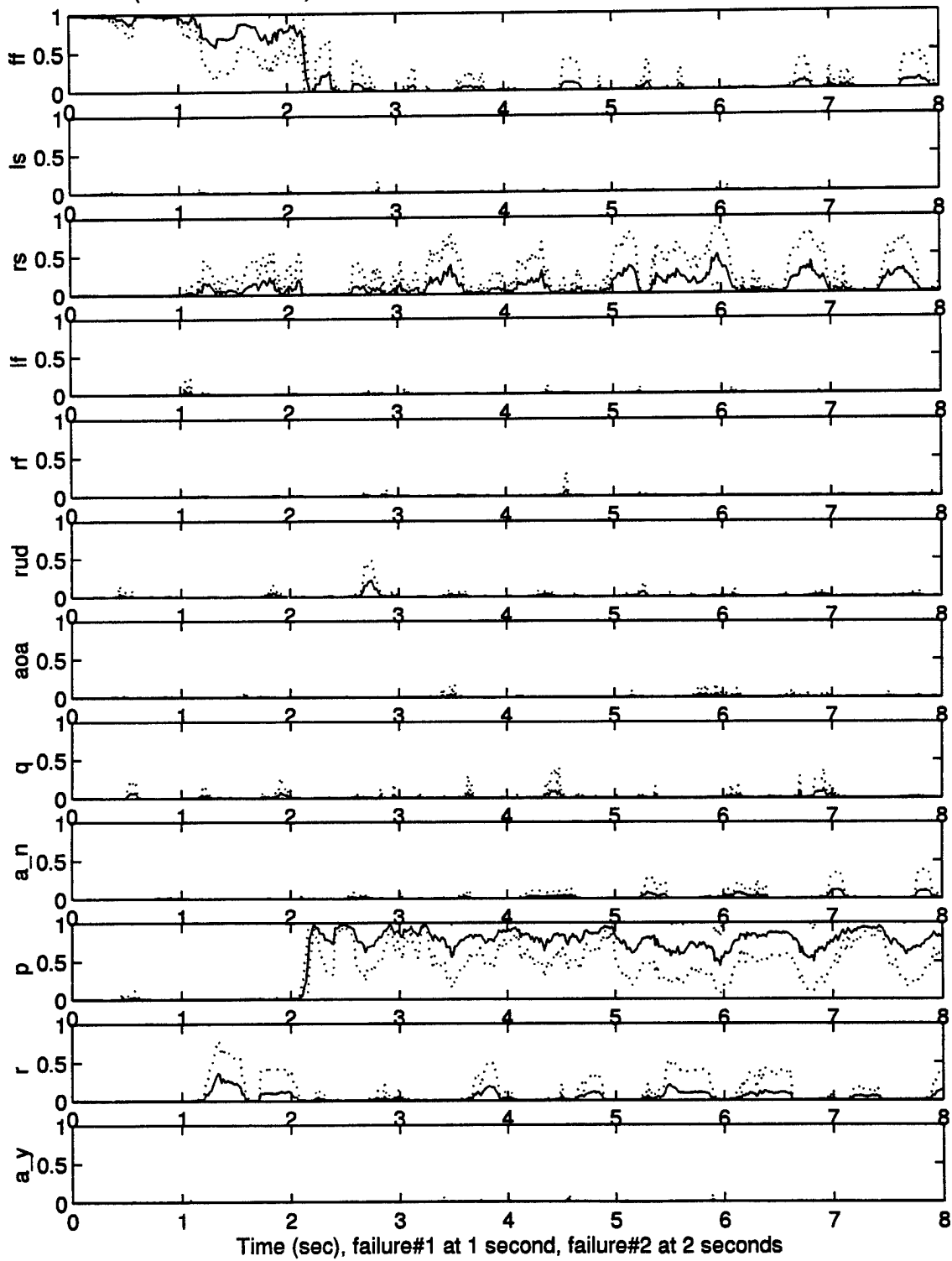
Mean (+/- One Std Dev) Dual-fail Probabilities of fail502.07 with reconfiguration: 10 runs



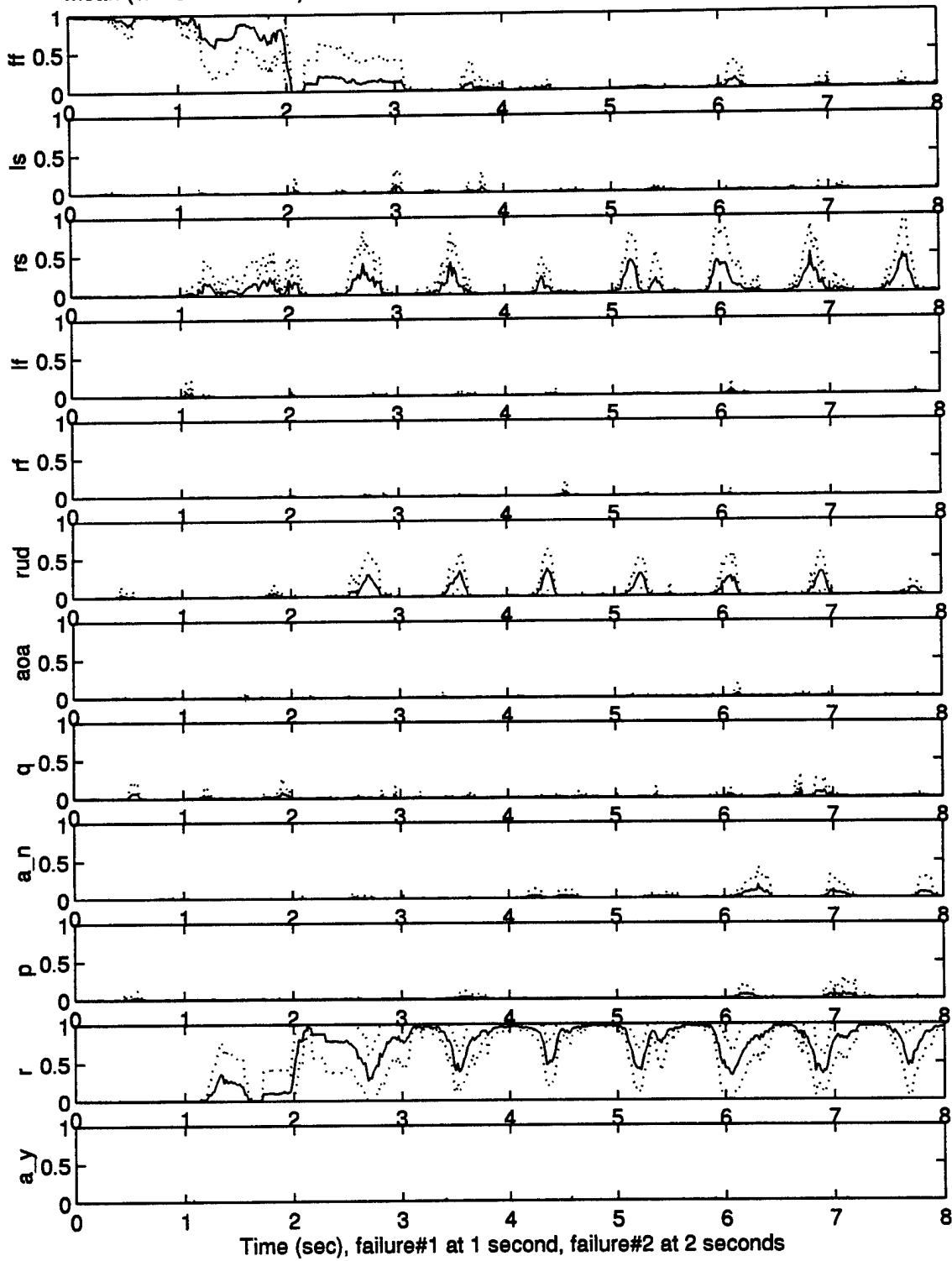
Mean (+/- One Std Dev) Dual-fail Probabilities of fail502.08 with reconfiguration: 10 runs



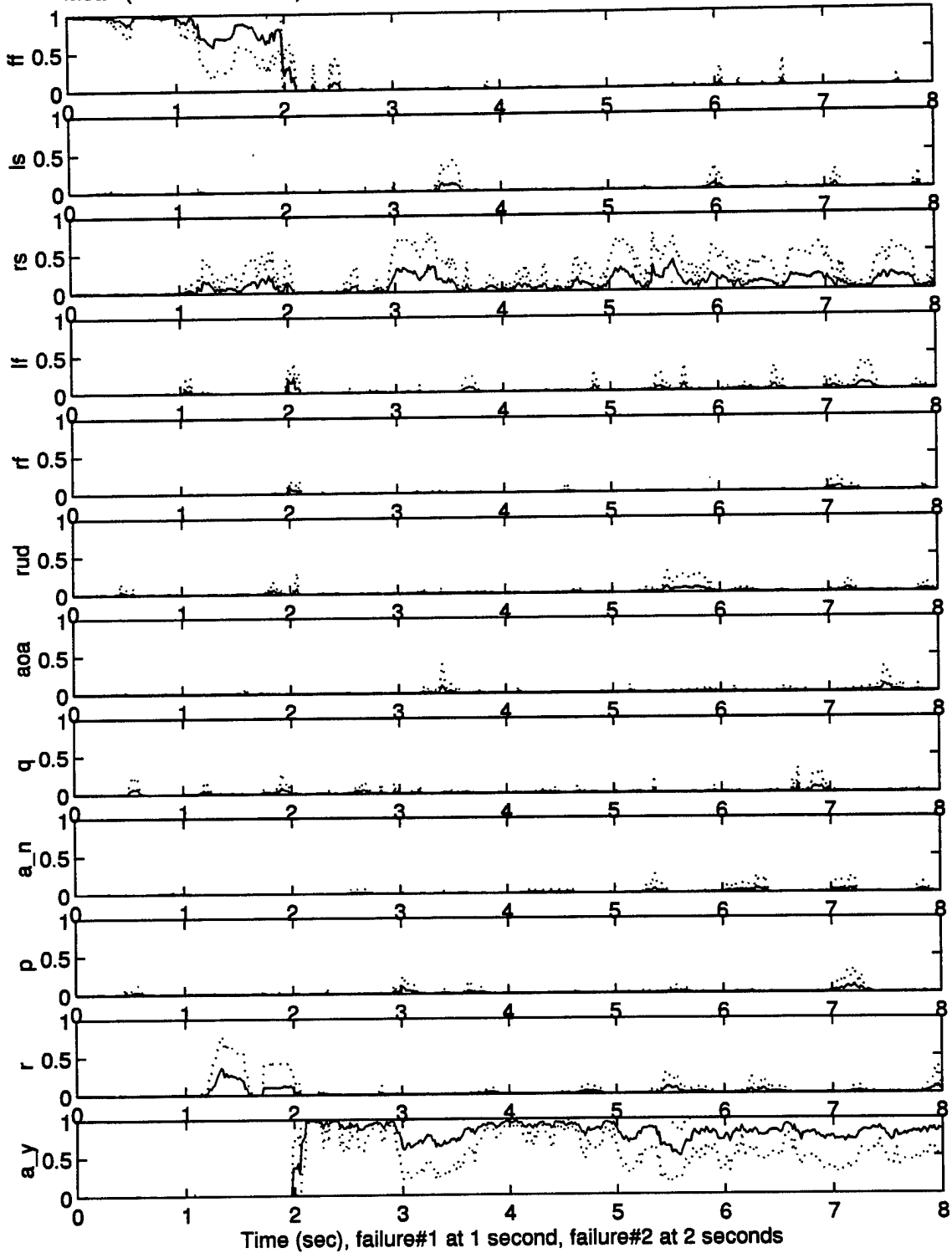
Mean (+/- One Std Dev) Dual-fail Probabilities of fail502.09 with reconfiguration: 10 runs



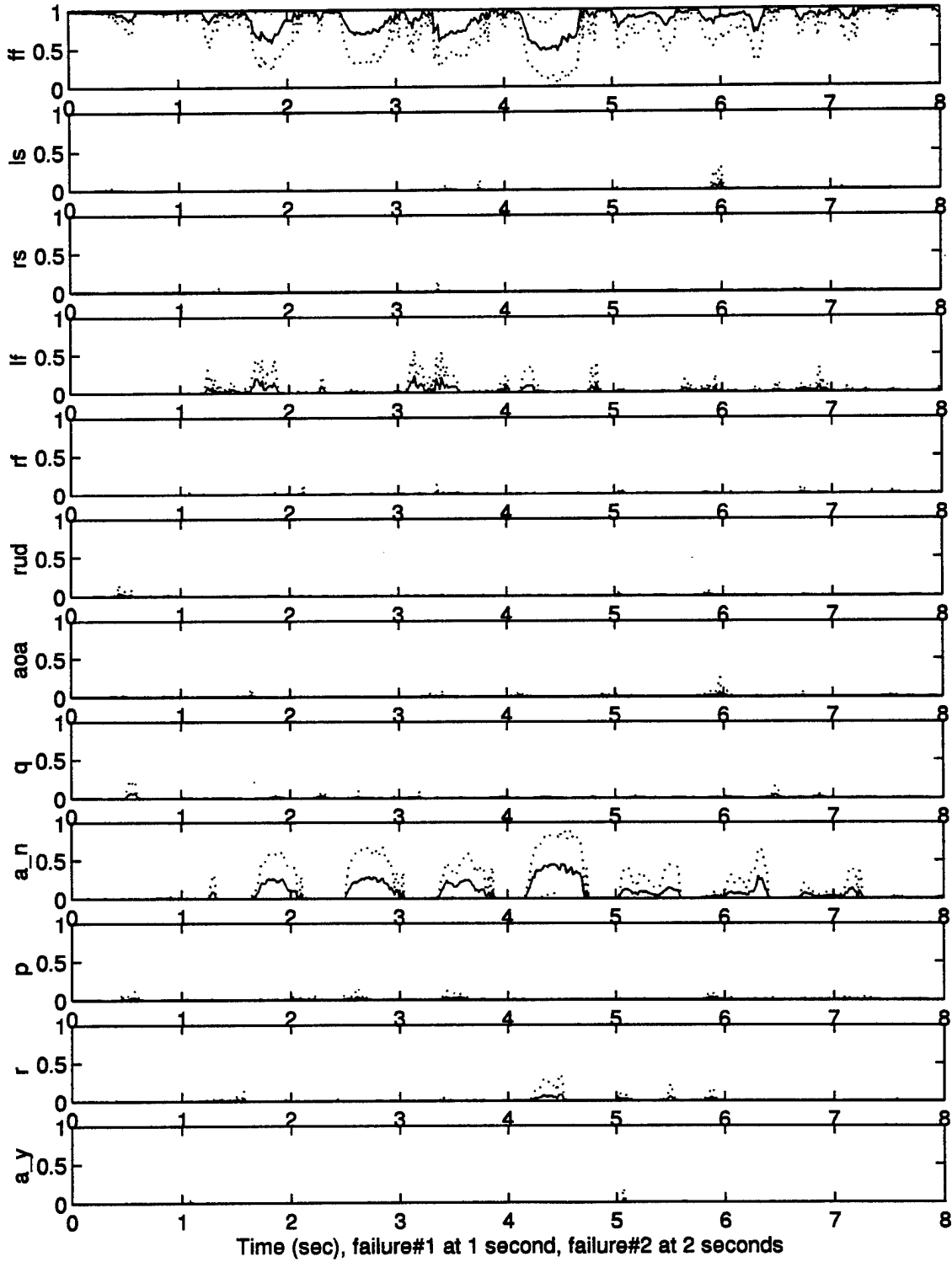
Mean (+/- One Std Dev) Dual-fail Probabilities of fail502.010 with reconfiguration: 10 runs



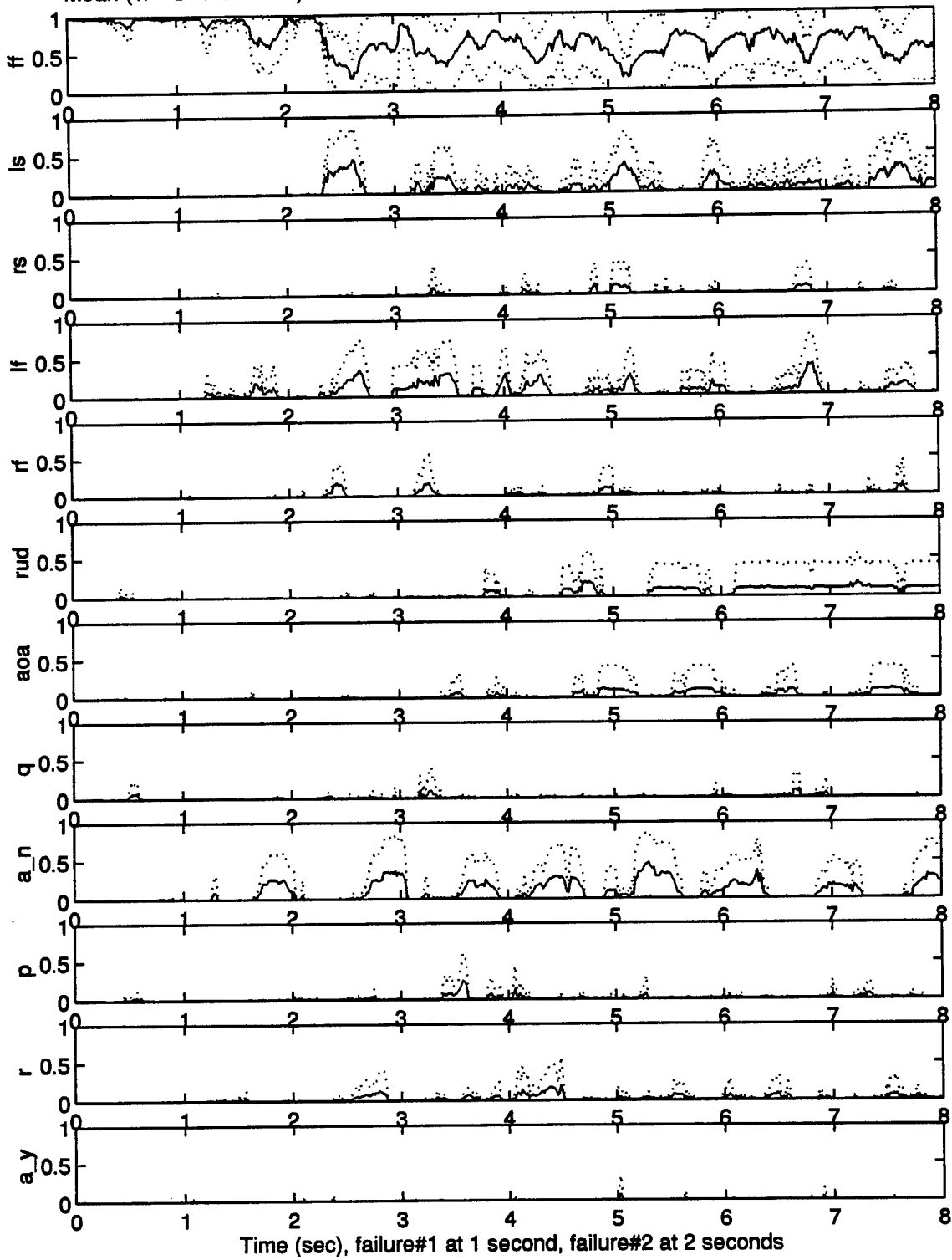
Mean (+/- One Std Dev) Dual-fail Probabilities of fail502.011 with reconfiguration: 10 runs



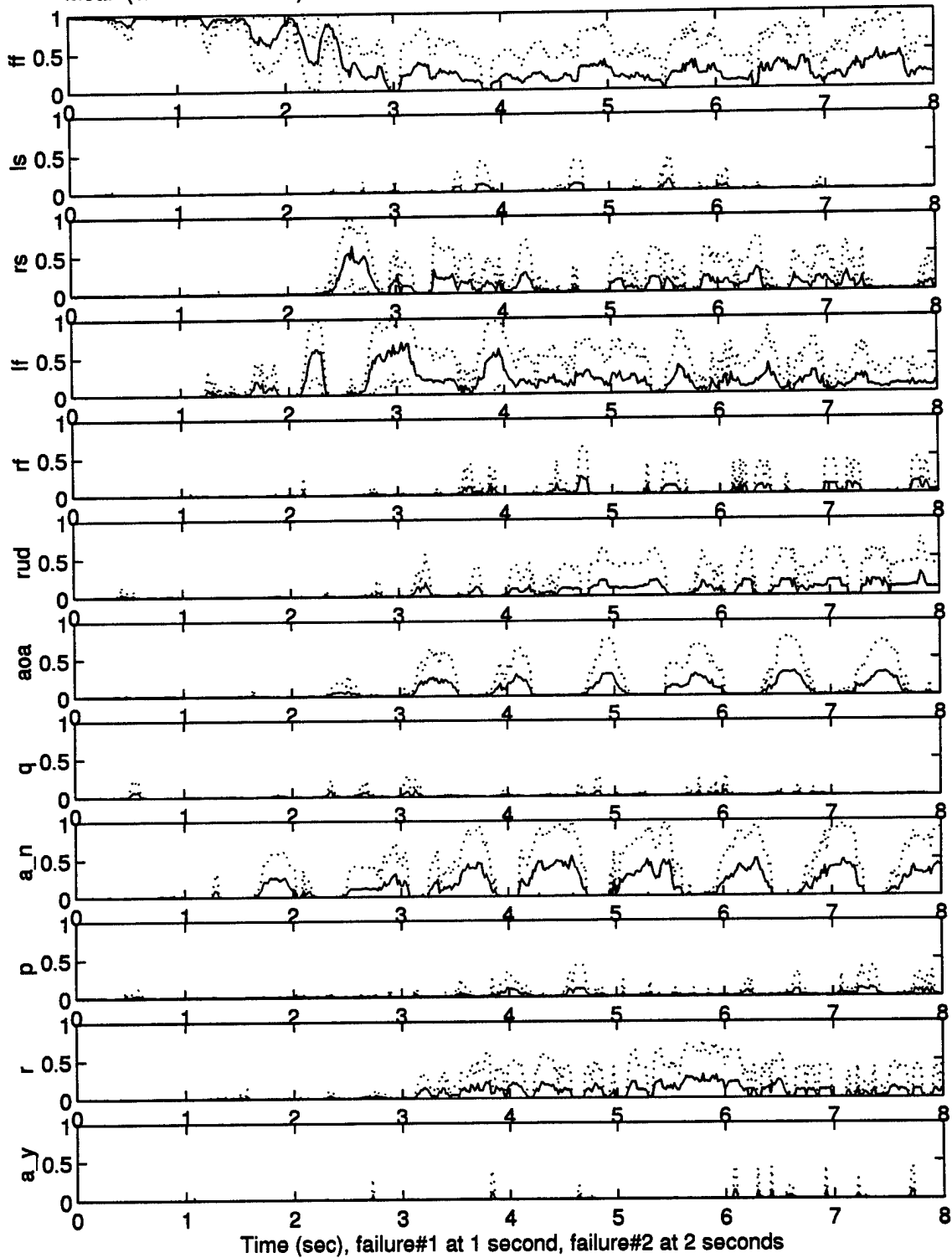
Mean (+/- One Std Dev) Dual-fail Probabilities of fail503.500 with reconfiguration: 10 runs



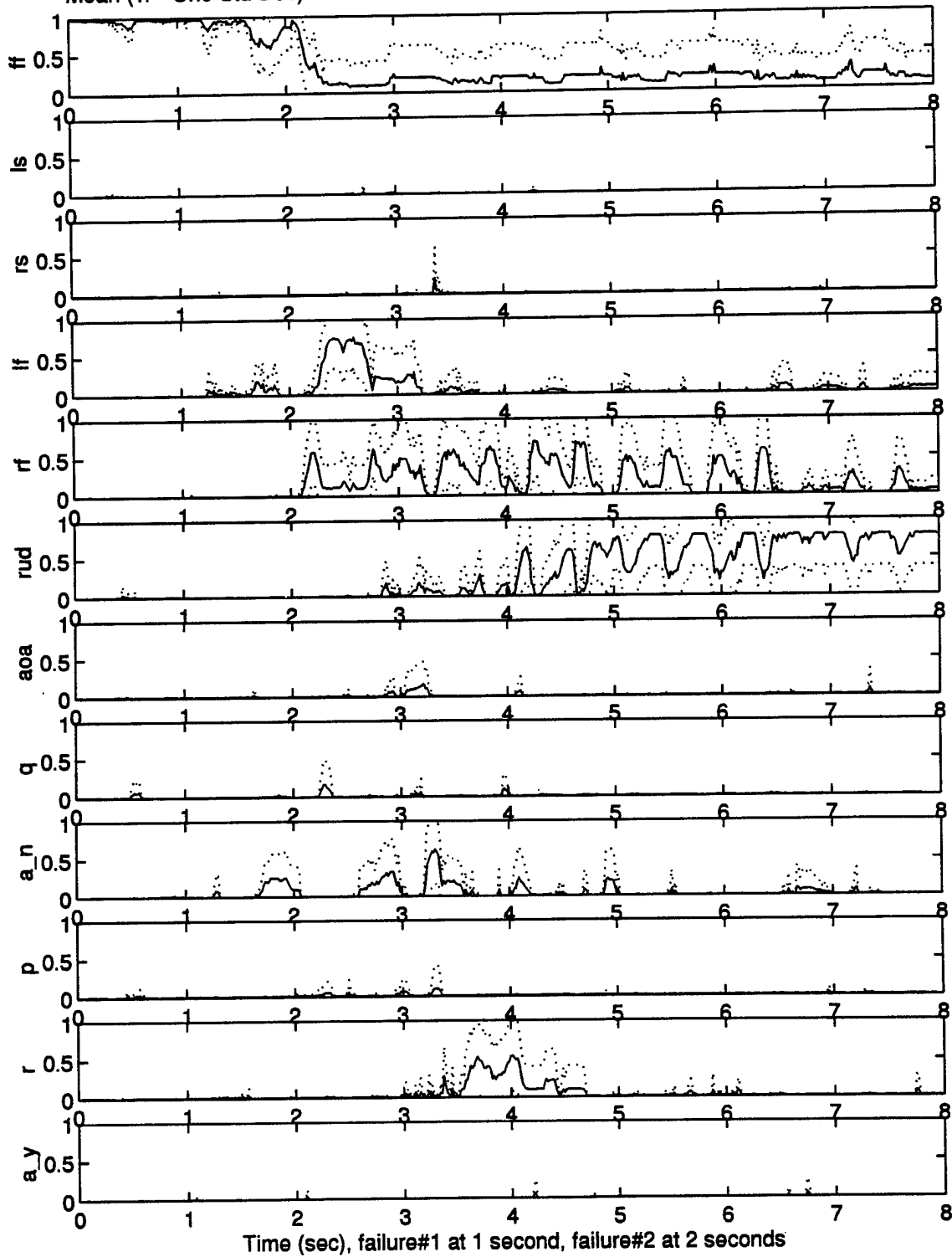
Mean (+/- One Std Dev) Dual-fail Probabilities of fail503.501 with reconfiguration: 10 runs



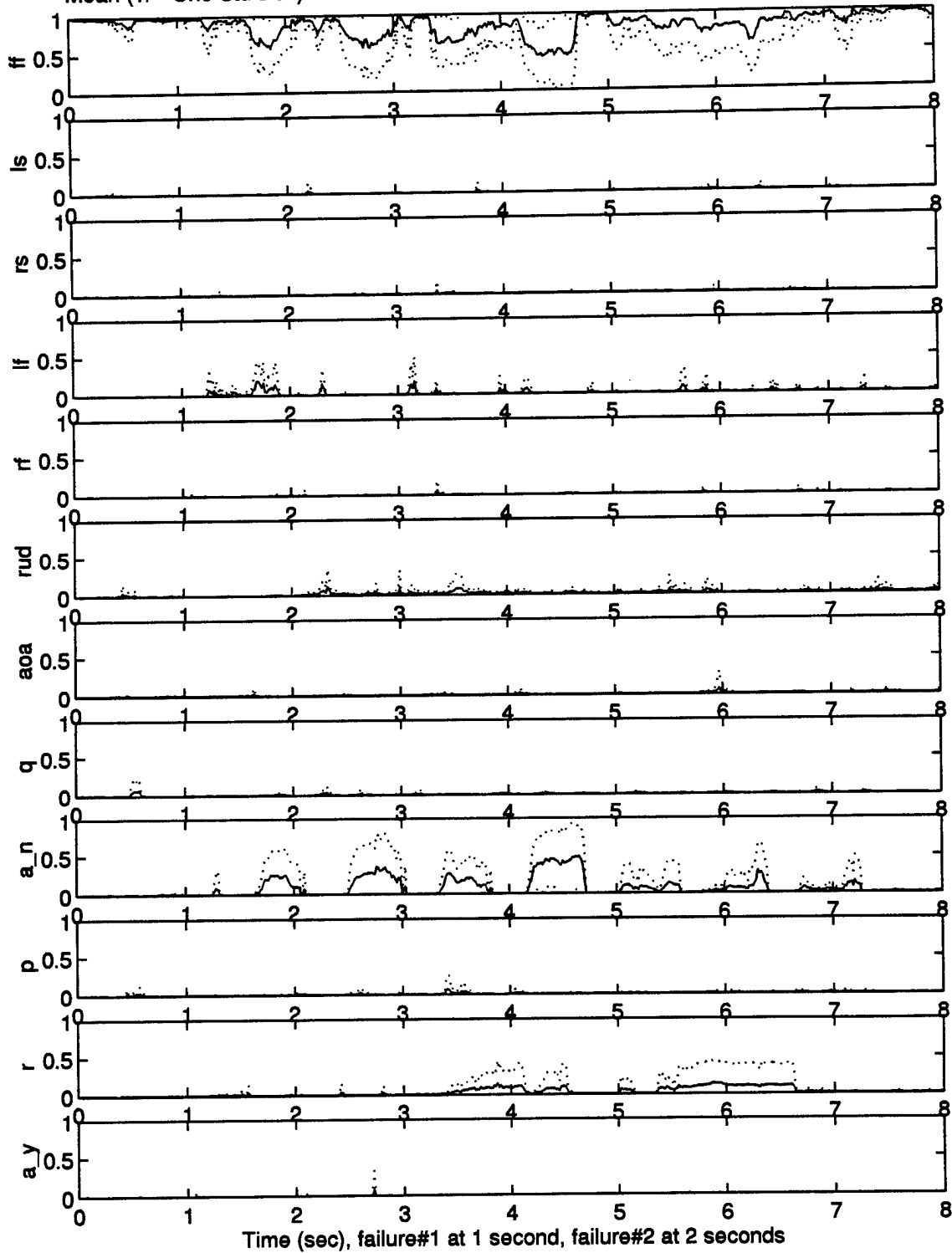
Mean (+/- One Std Dev) Dual-fail Probabilities of fail503.502 with reconfiguration: 10 runs



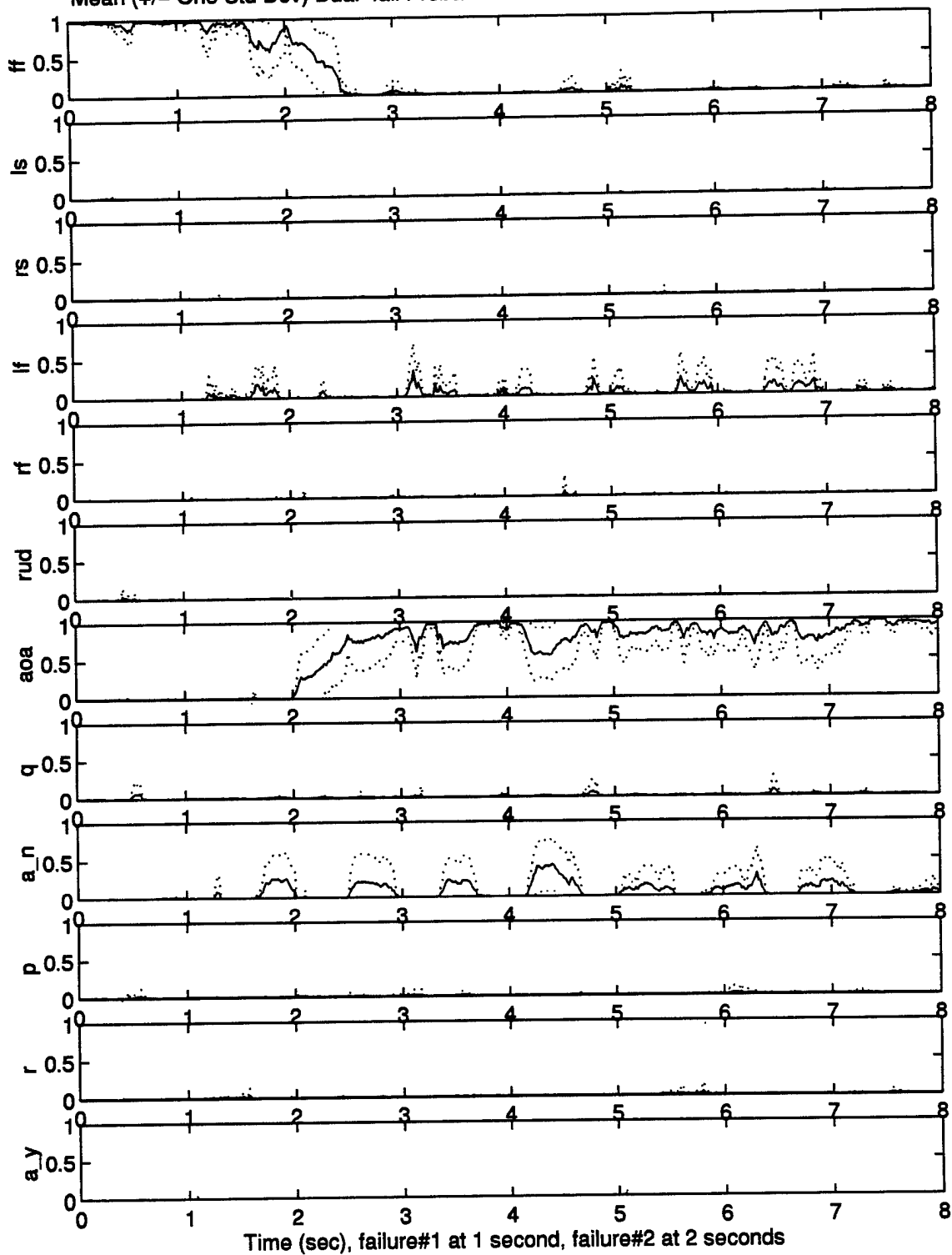
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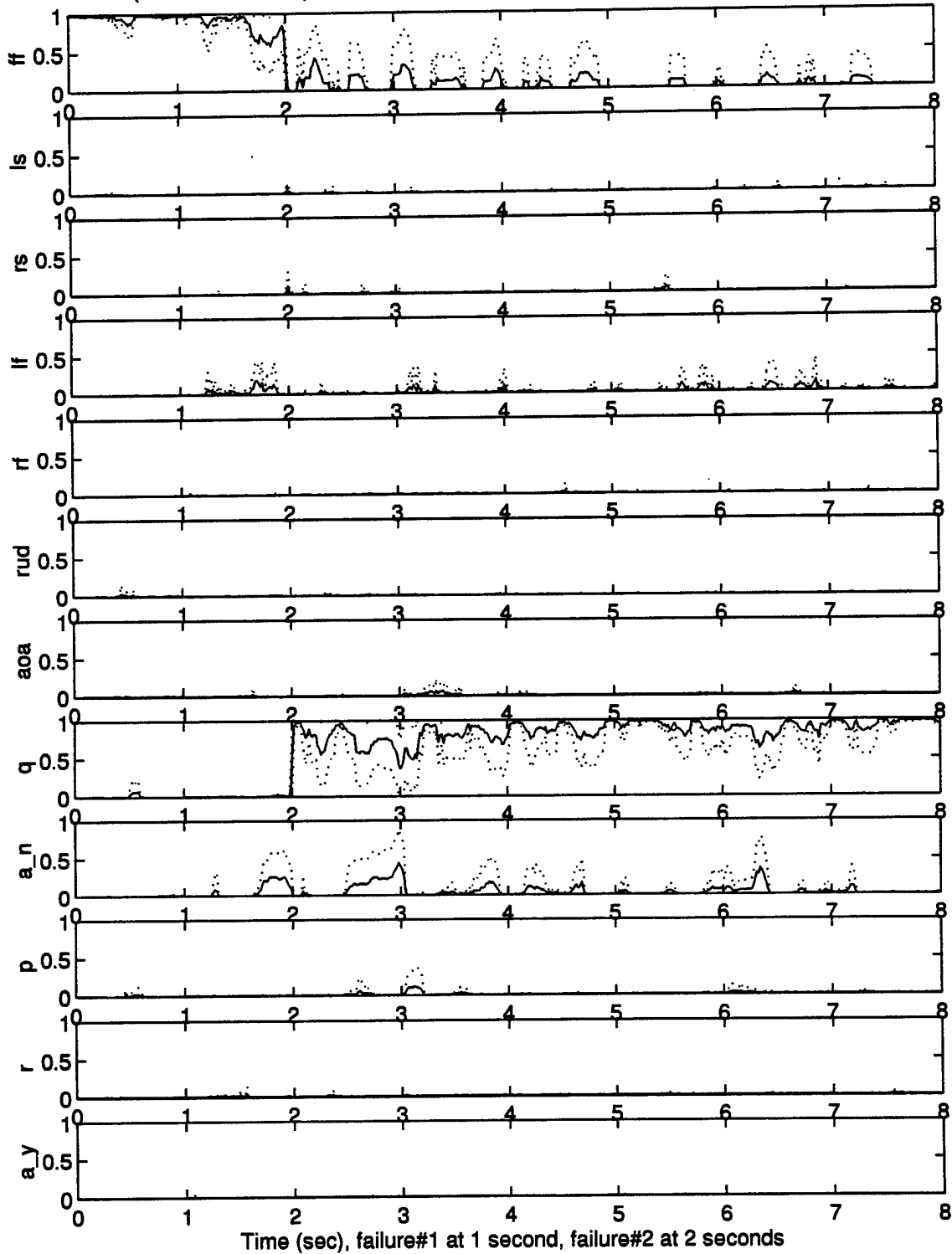
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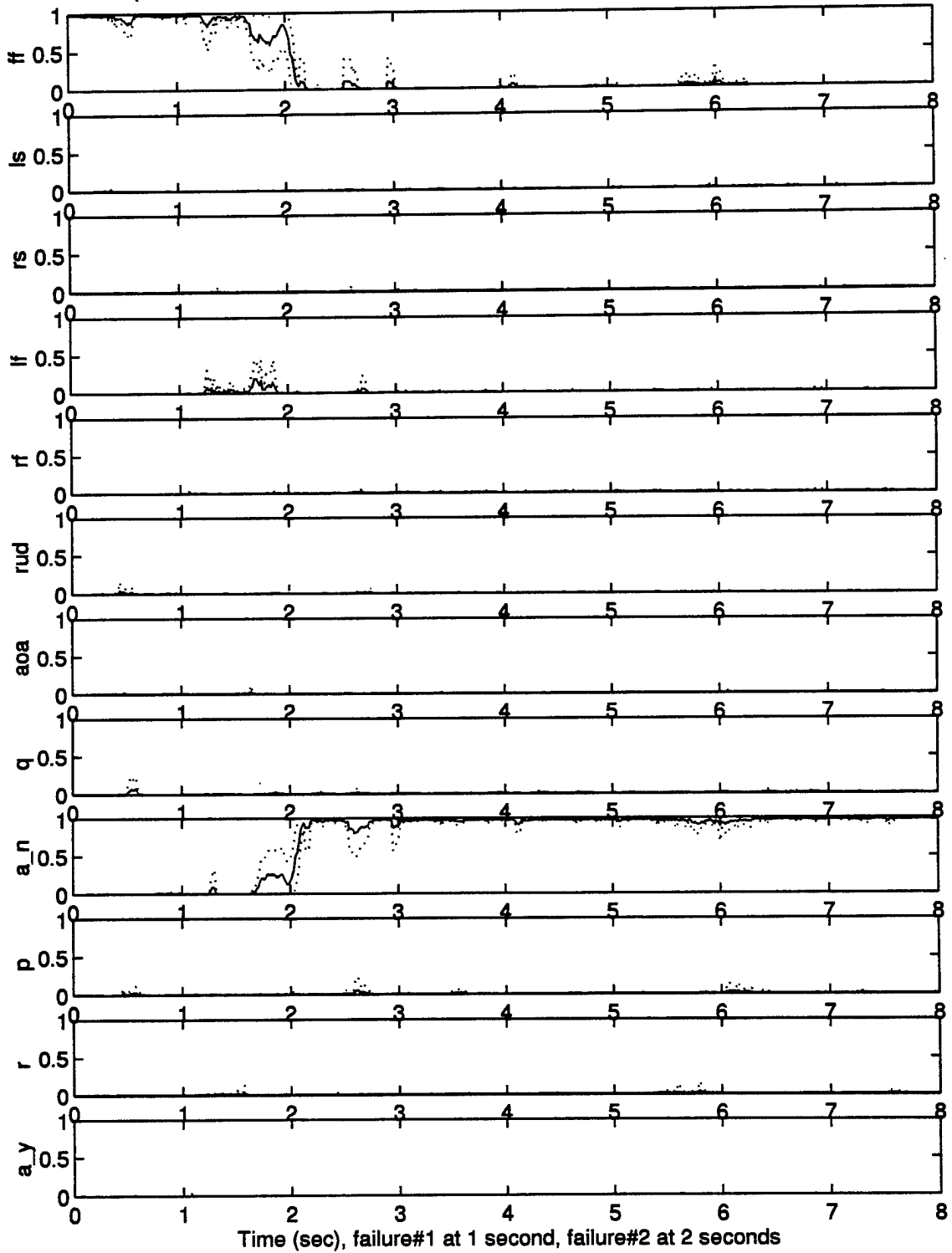
Mean (+/- One Std Dev) Dual-fail Probabilities of fail503.06 with reconfiguration: 10 runs



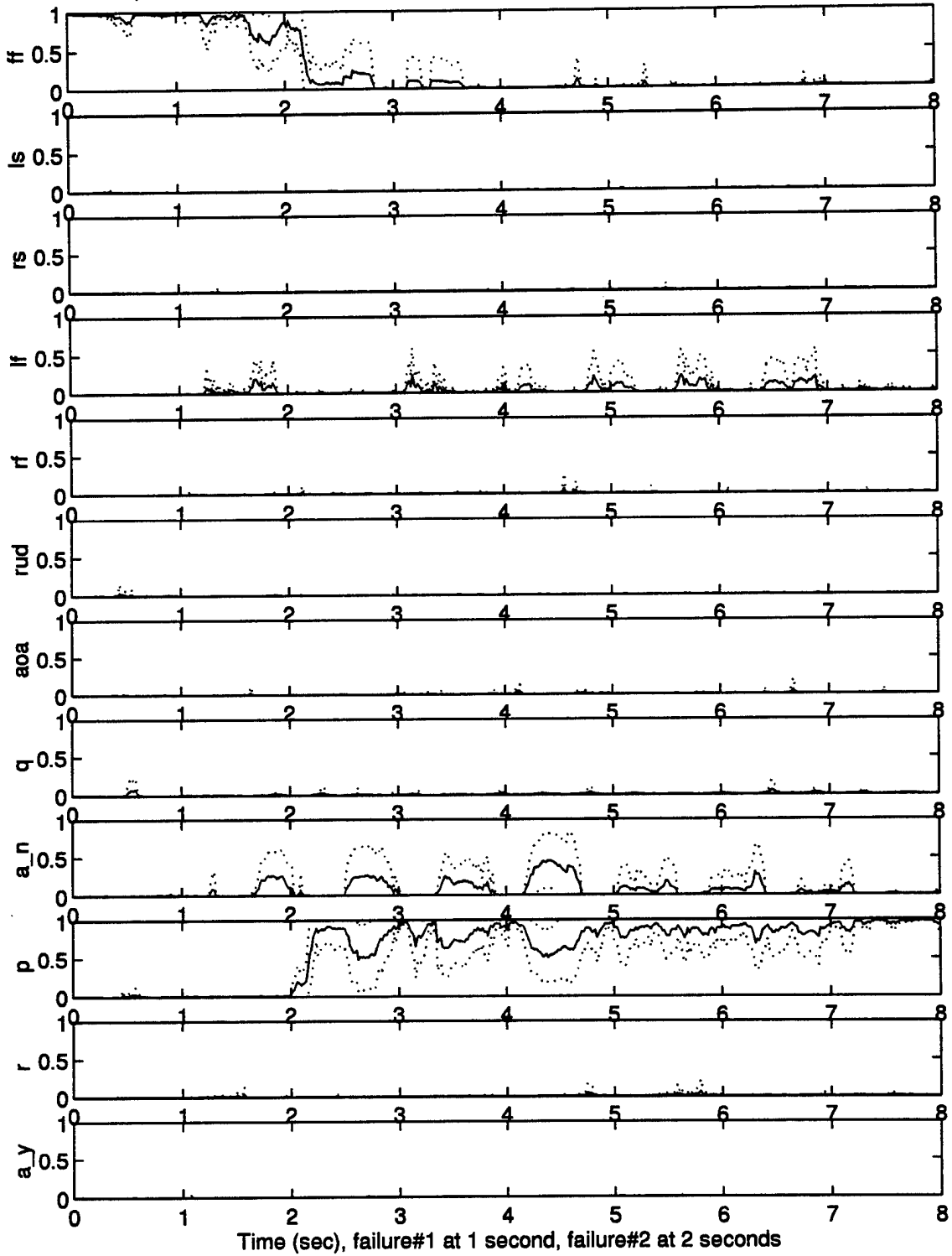
Mean (+/- One Std Dev) Dual-fail Probabilities of fail503.07 with reconfiguration: 10 runs



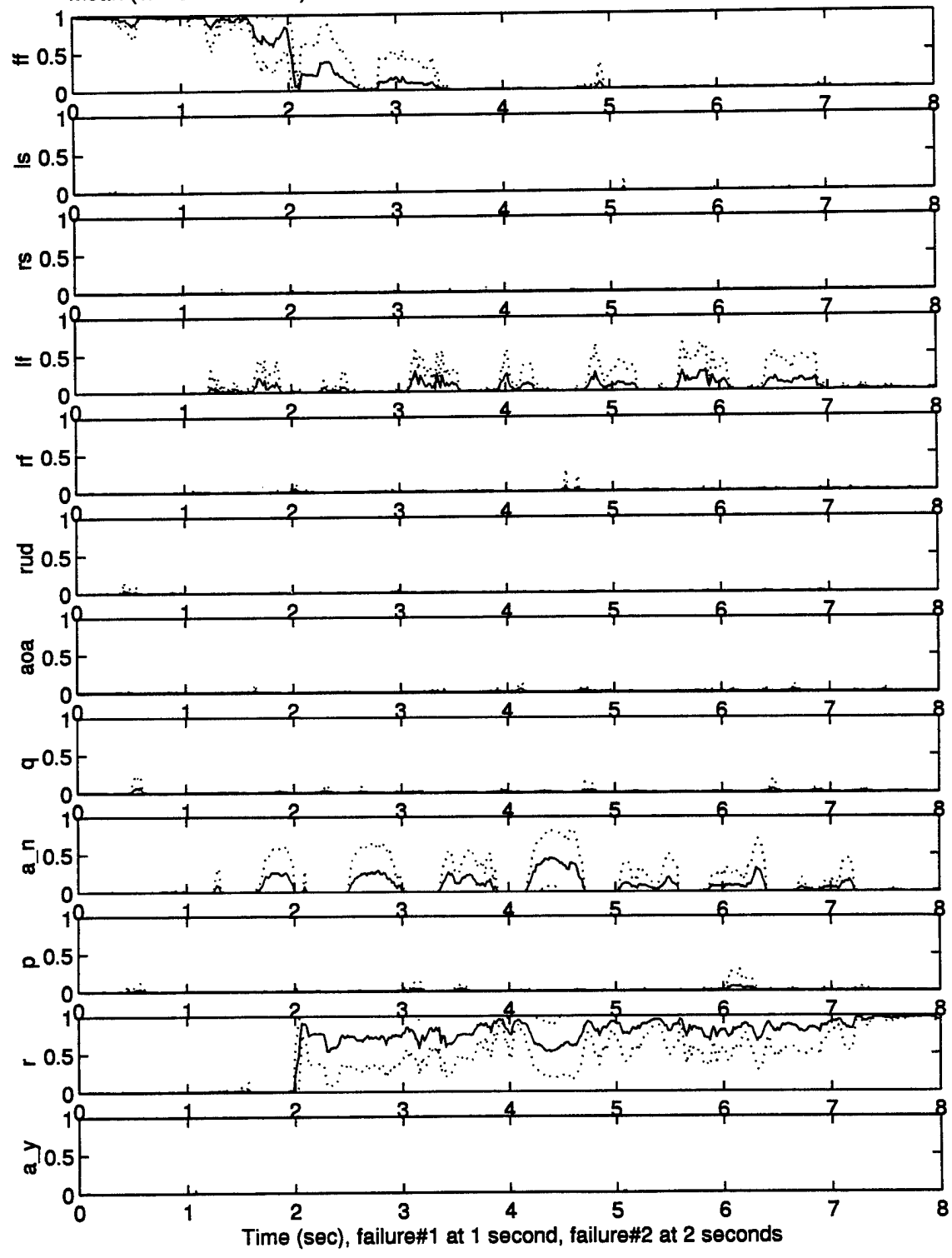
Mean (+/- One Std Dev) Dual-fail Probabilities of fail503.08 with reconfiguration: 10 runs



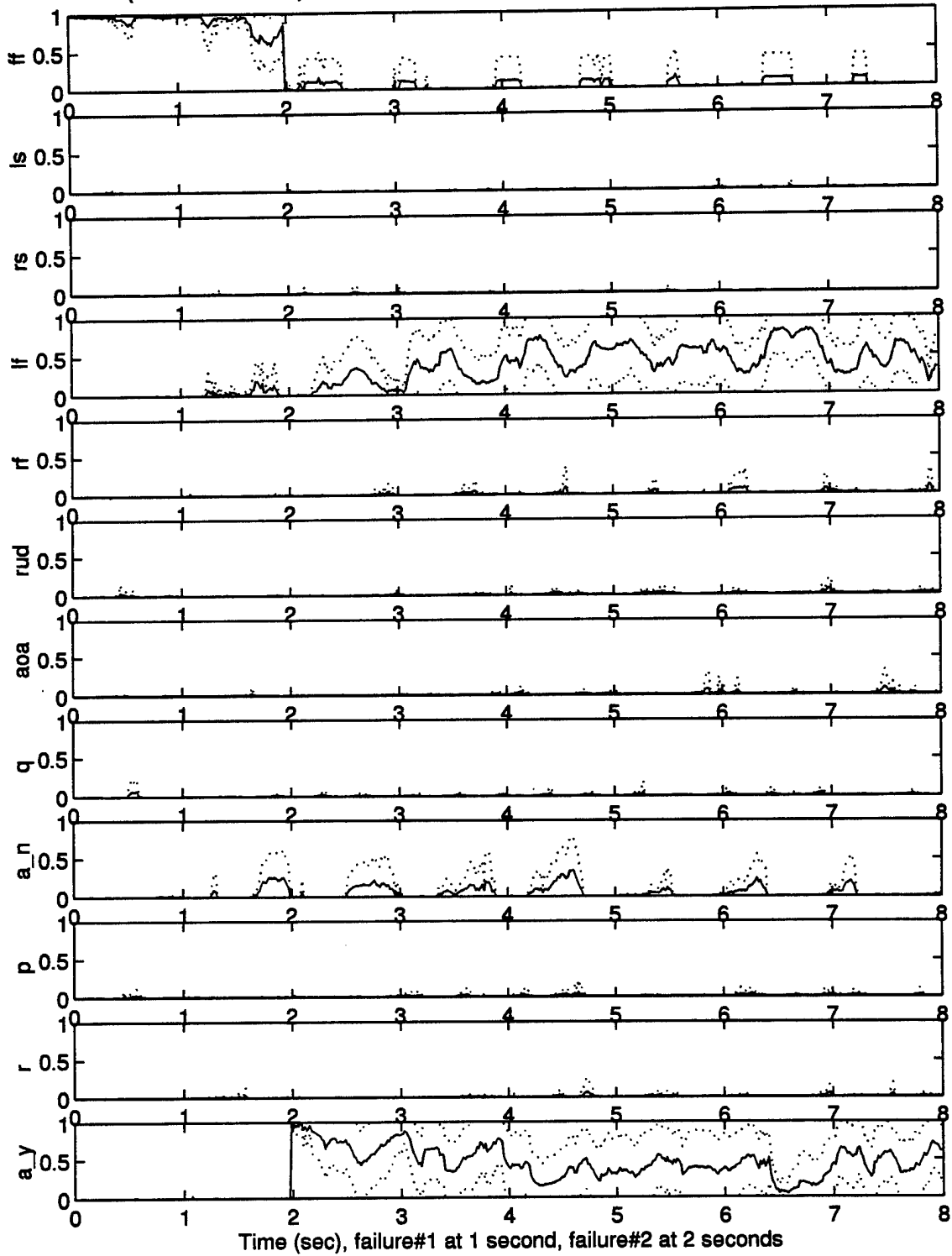
Mean (+/- One Std Dev) Dual-fail Probabilities of fail503.09 with reconfiguration: 10 runs



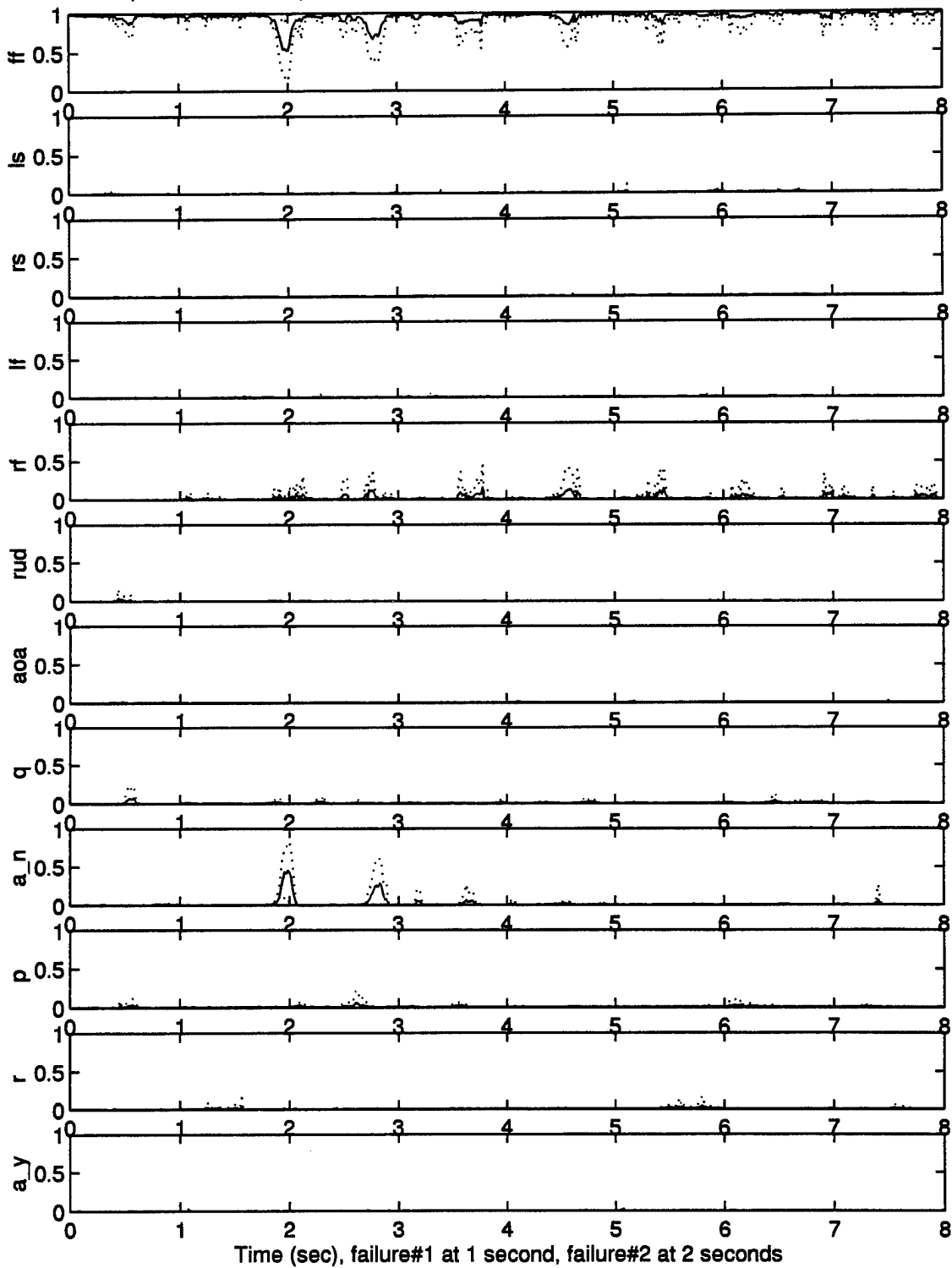
Mean (+/- One Std Dev) Dual-fail Probabilities of fail503.010 with reconfiguration: 10 runs



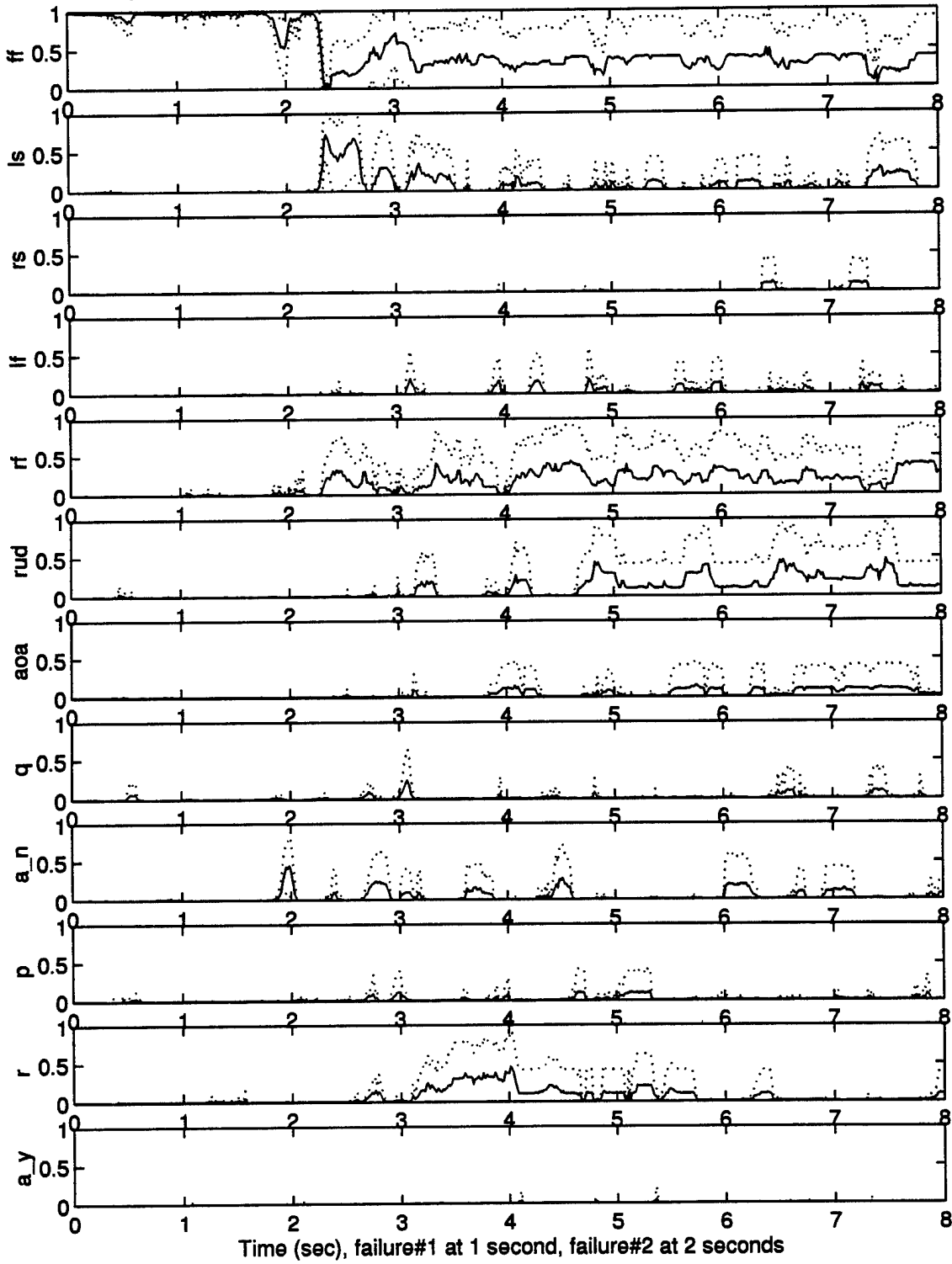
Mean (+/- One Std Dev) Dual-fail Probabilities of fail503.011 with reconfiguration: 10 runs



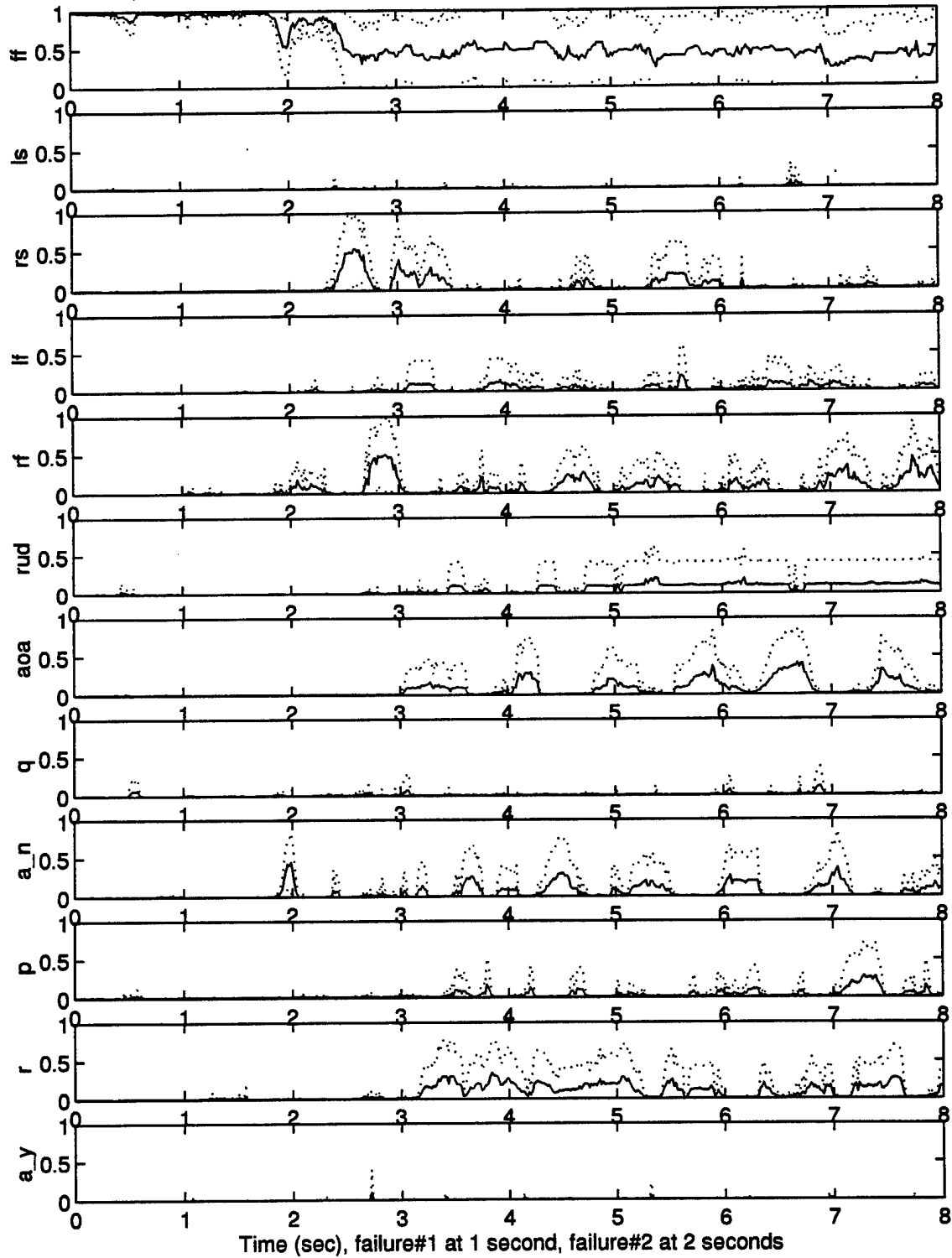
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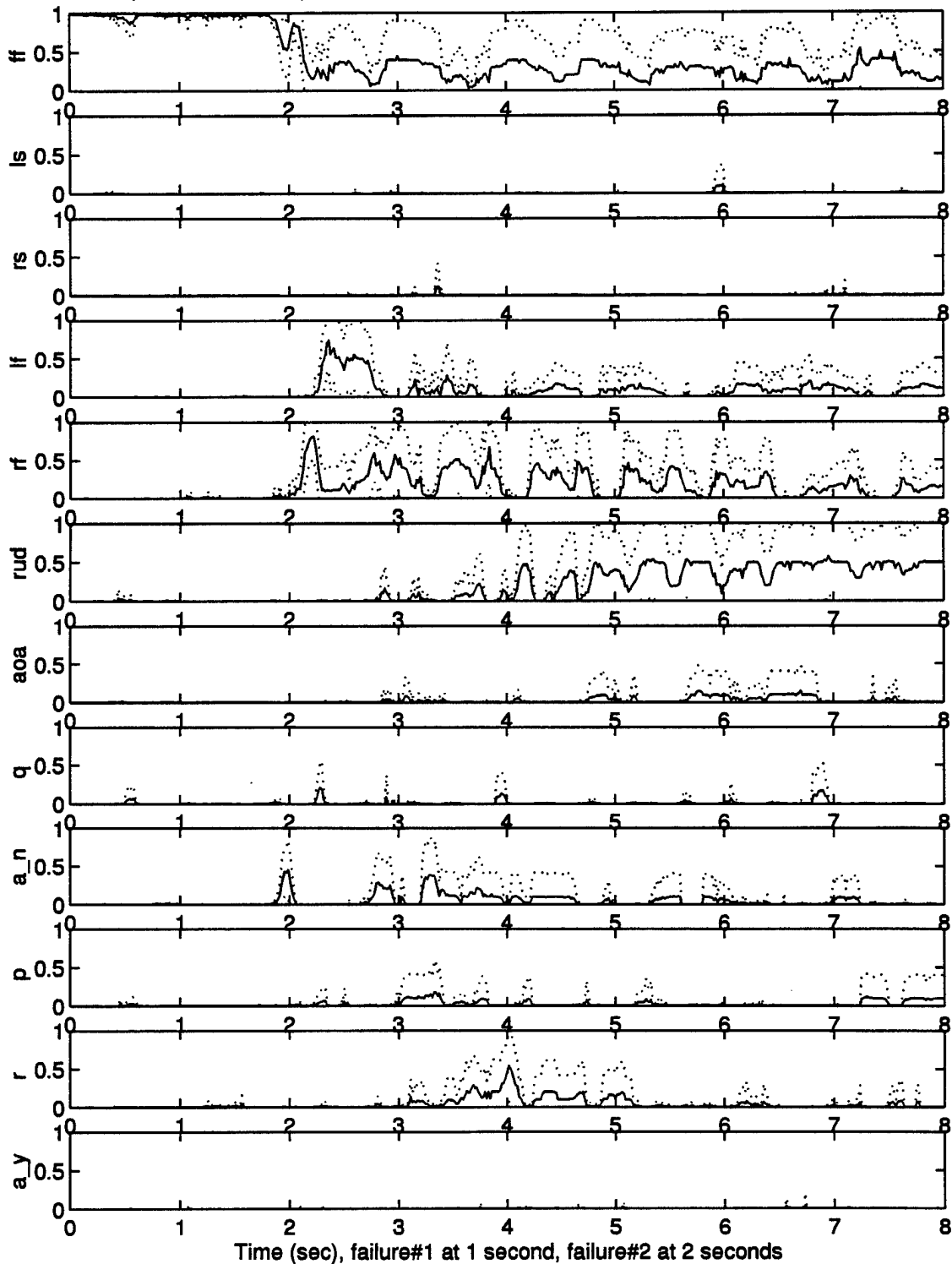
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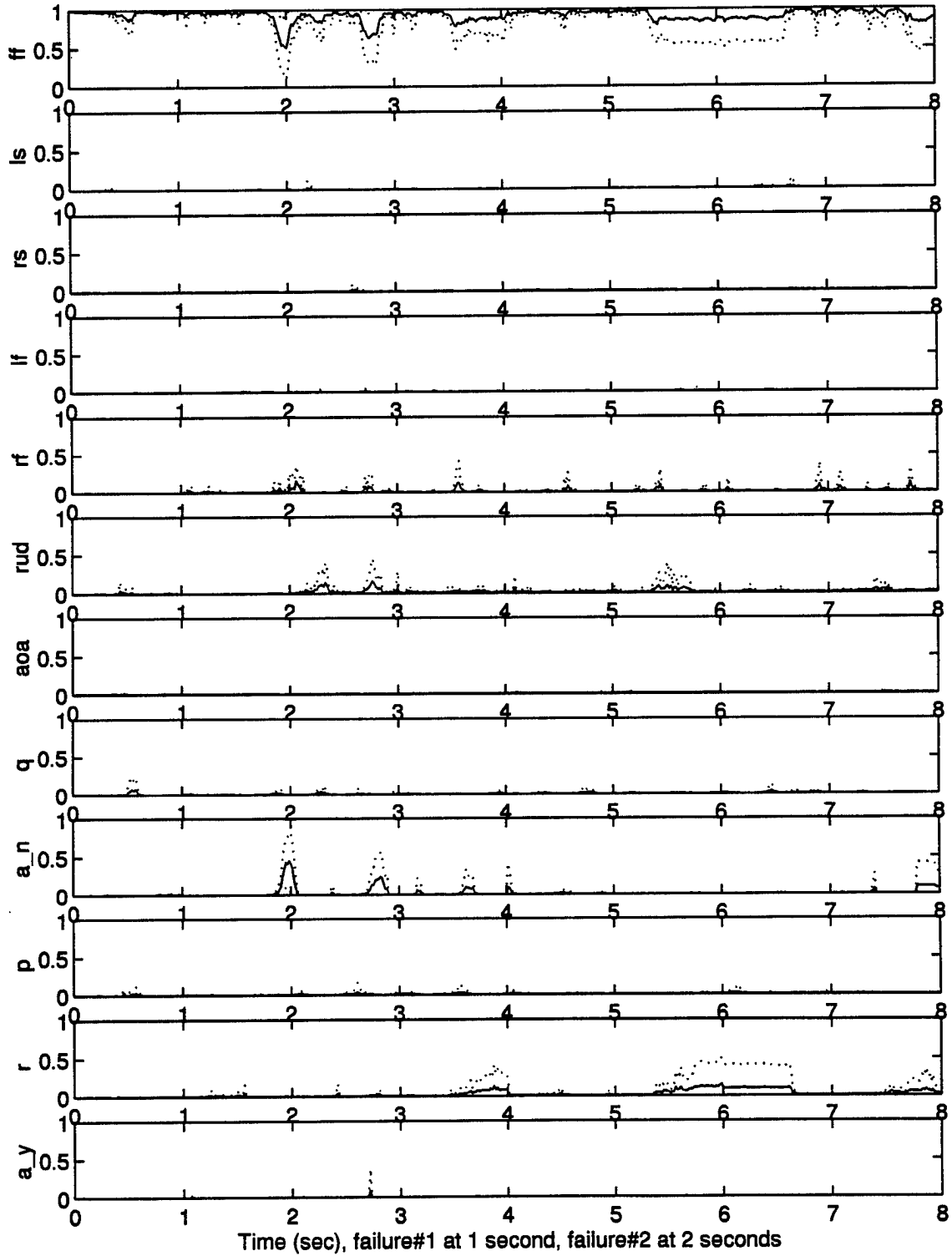
Mean (+/- One Std Dev) Dual-fail Probabilities of fail504.502 with reconfiguration: 10 runs



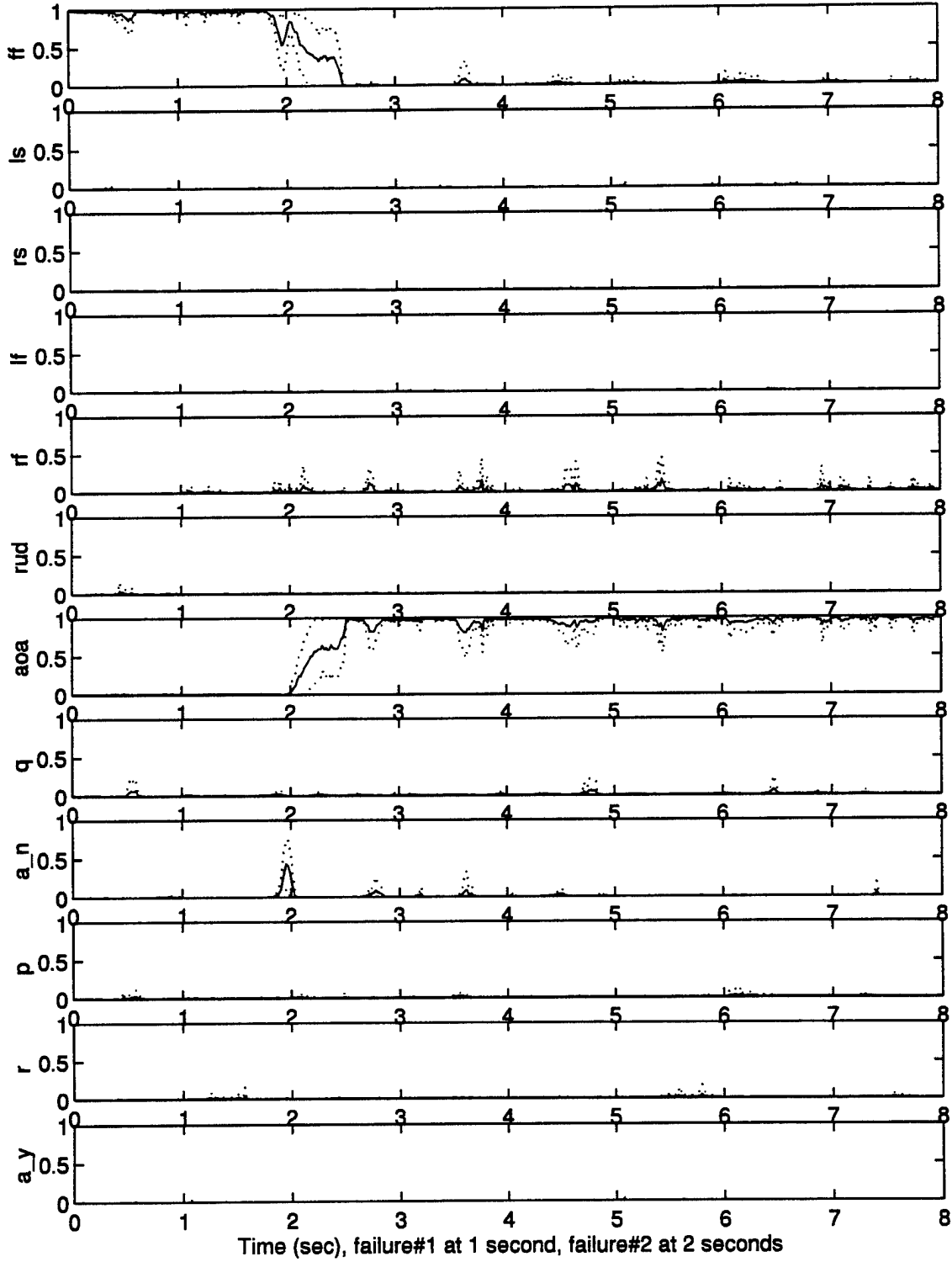
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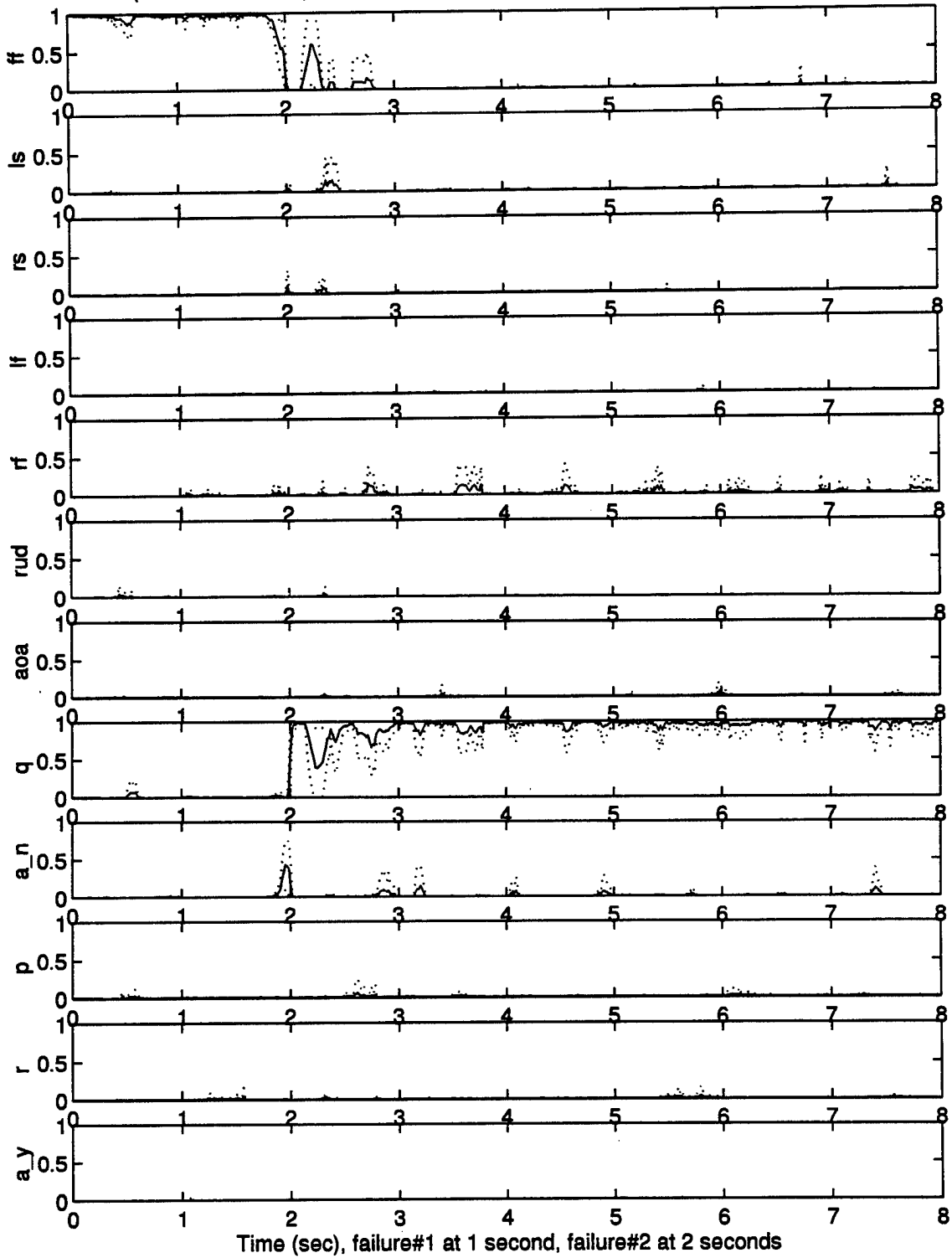
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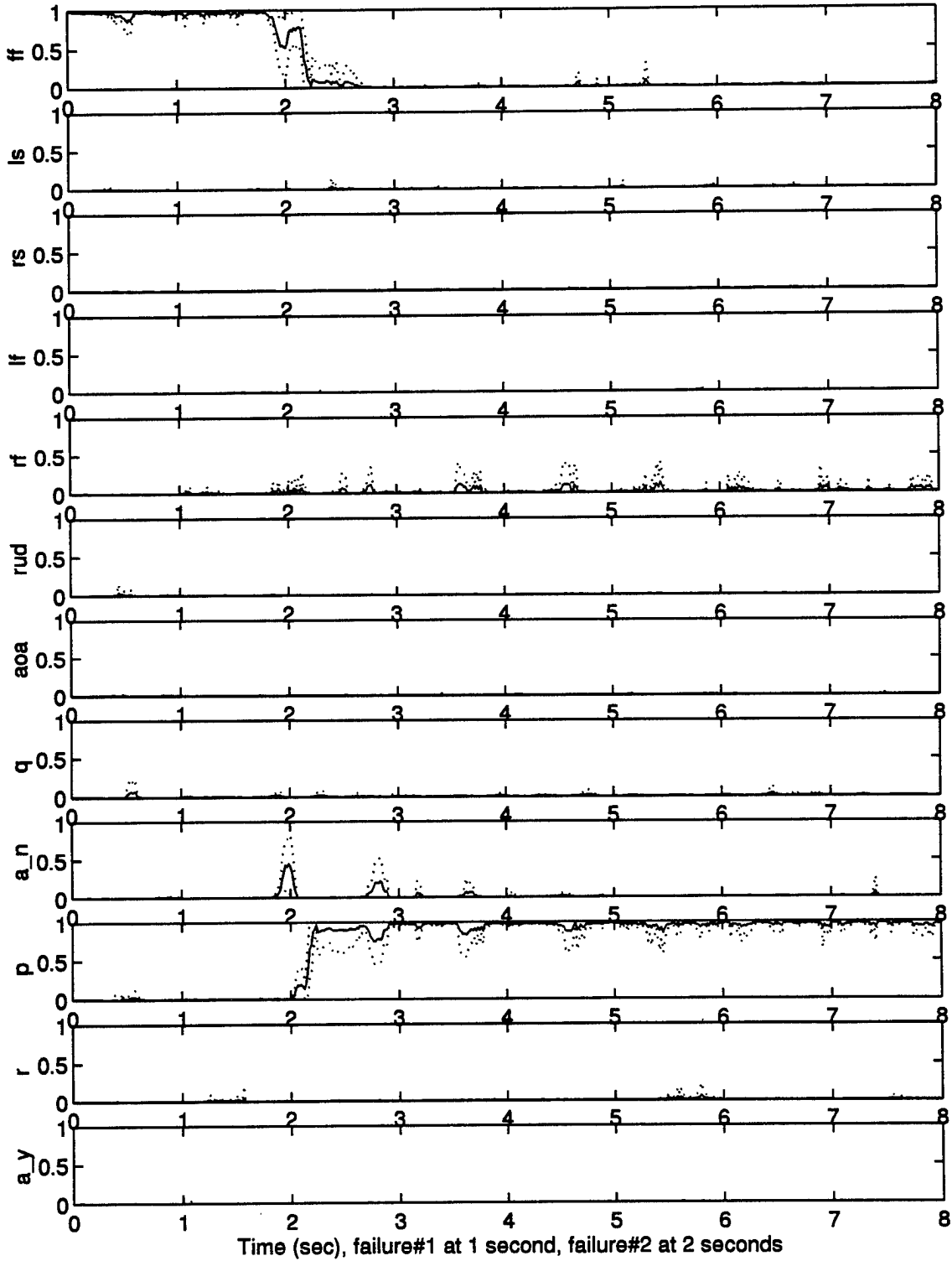
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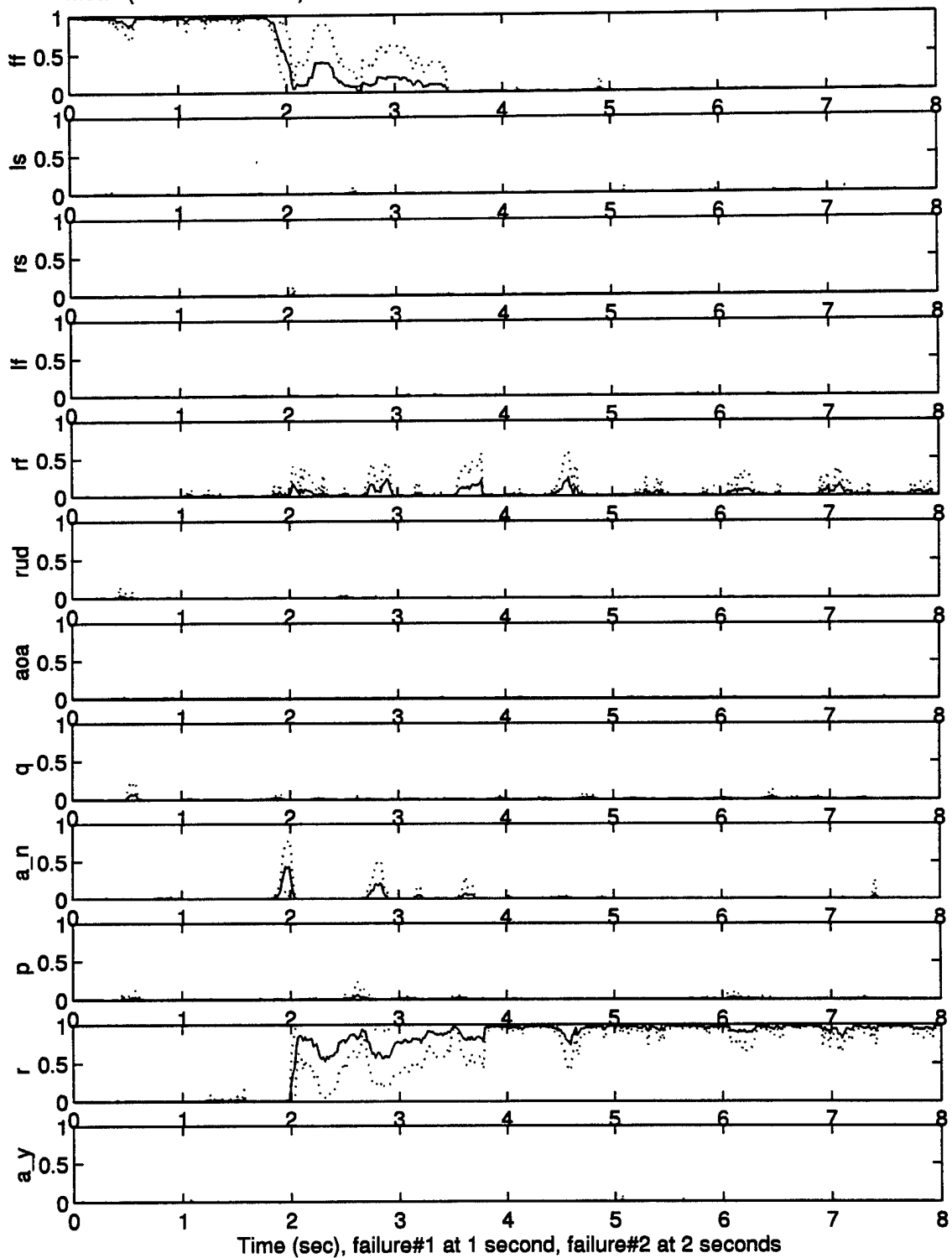
Mean (+/- One Std Dev) Dual-fail Probabilities of fail504.07 with reconfiguration: 10 runs



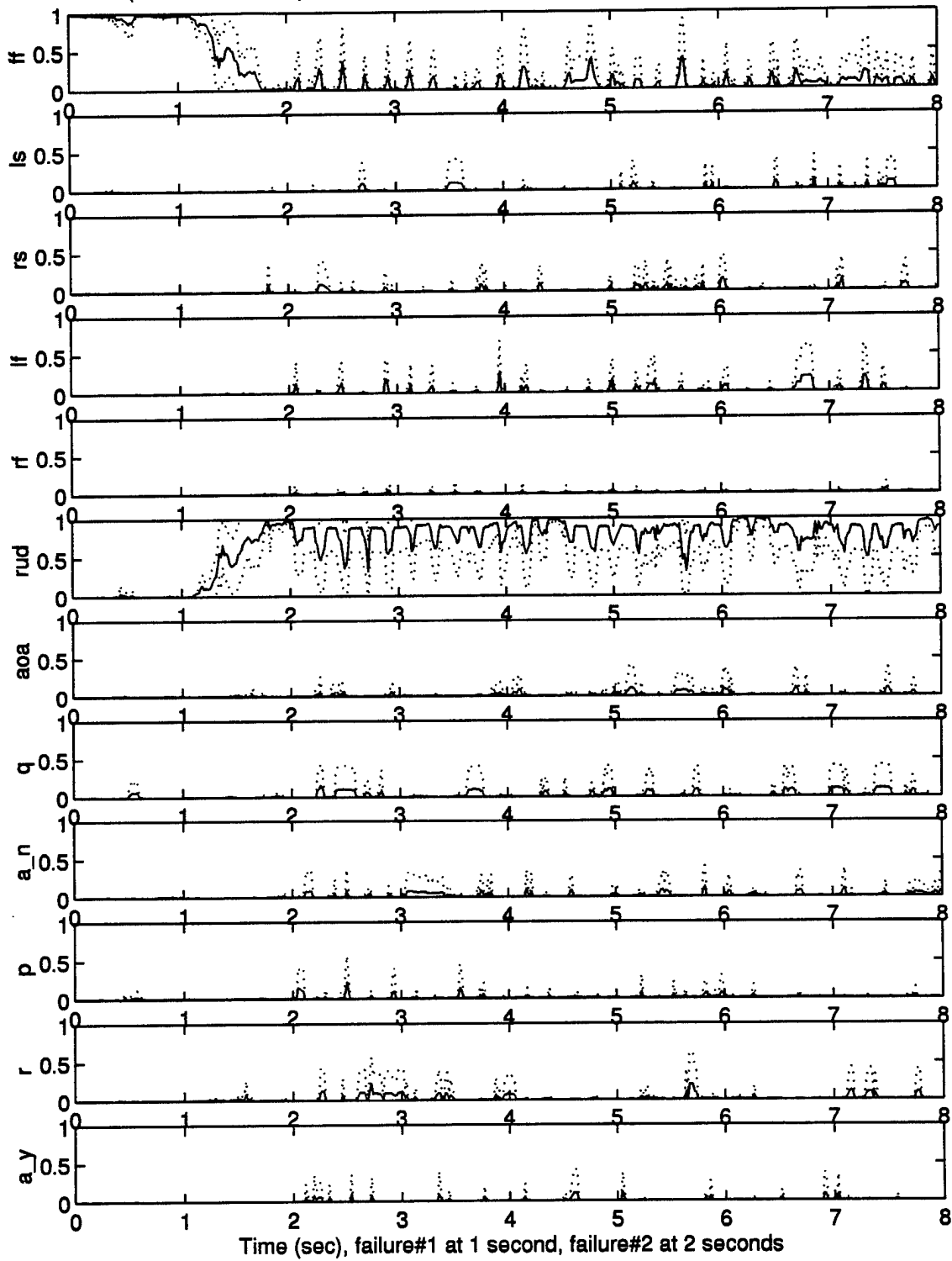
Mean (+/- One Std Dev) Dual-fail Probabilities of fail504.09 with reconfiguration: 10 runs



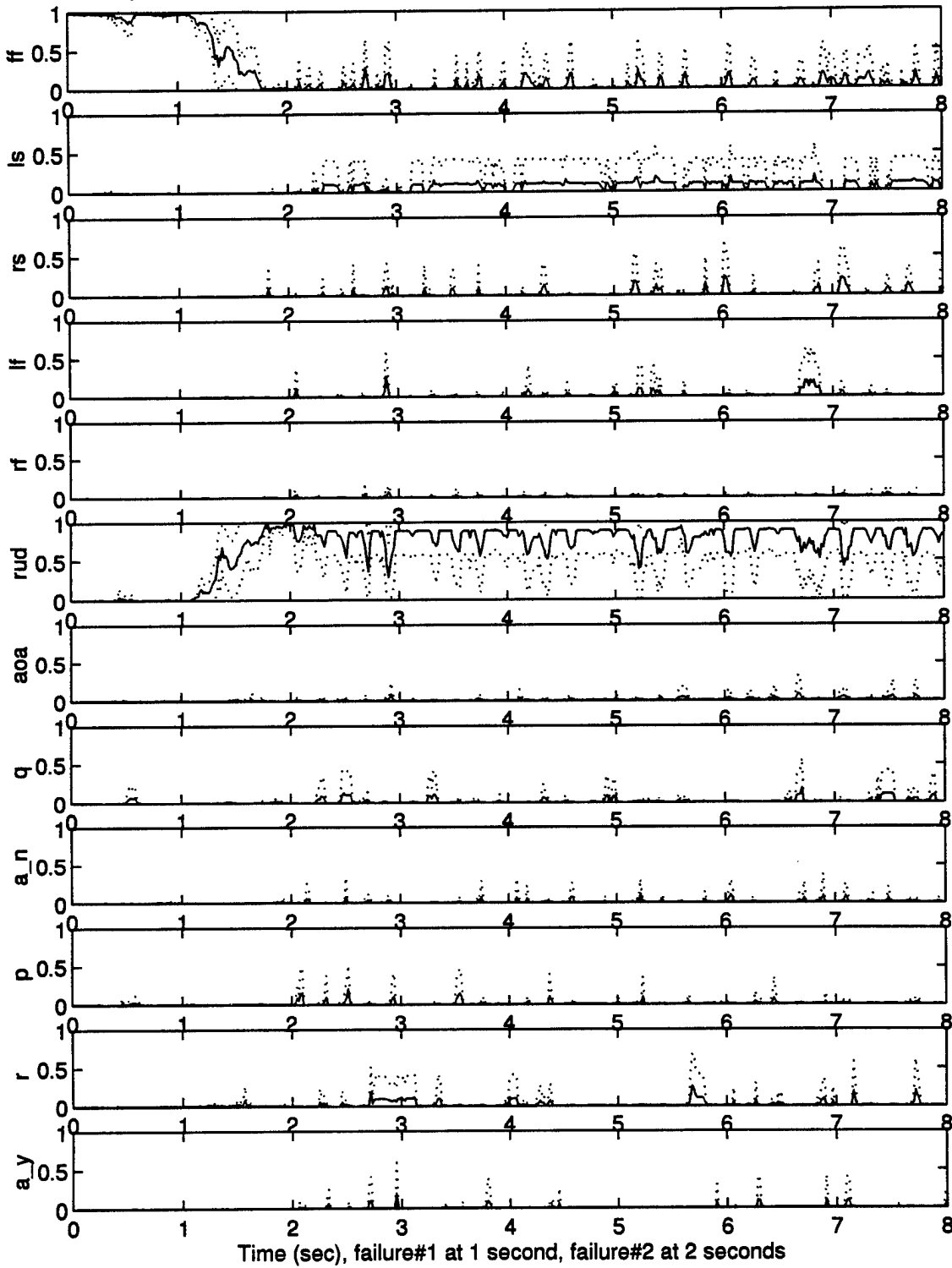
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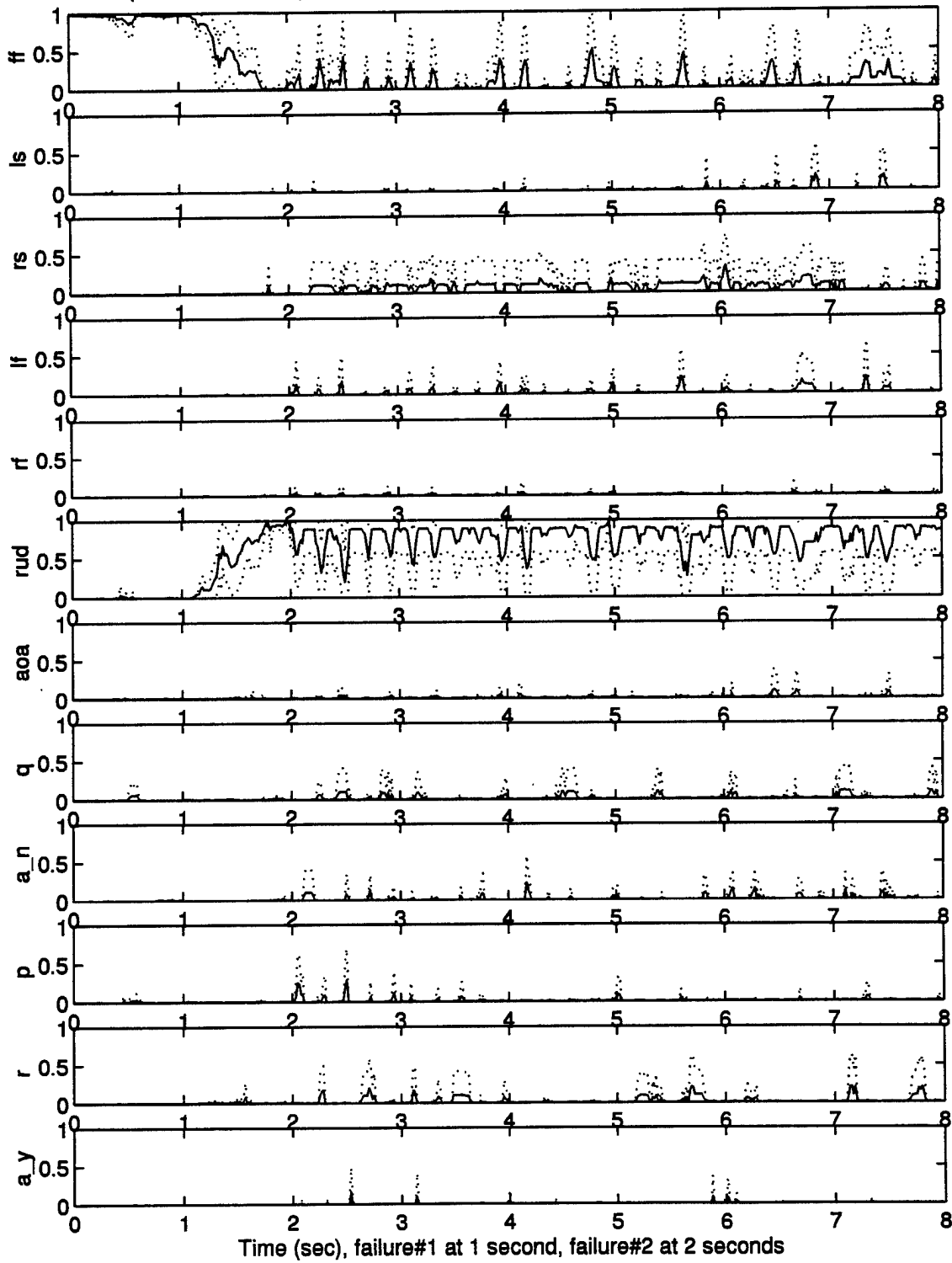
Mean (+/- One Std Dev) Dual-fail Probabilities of fail505.500 with reconfiguration: 10 runs



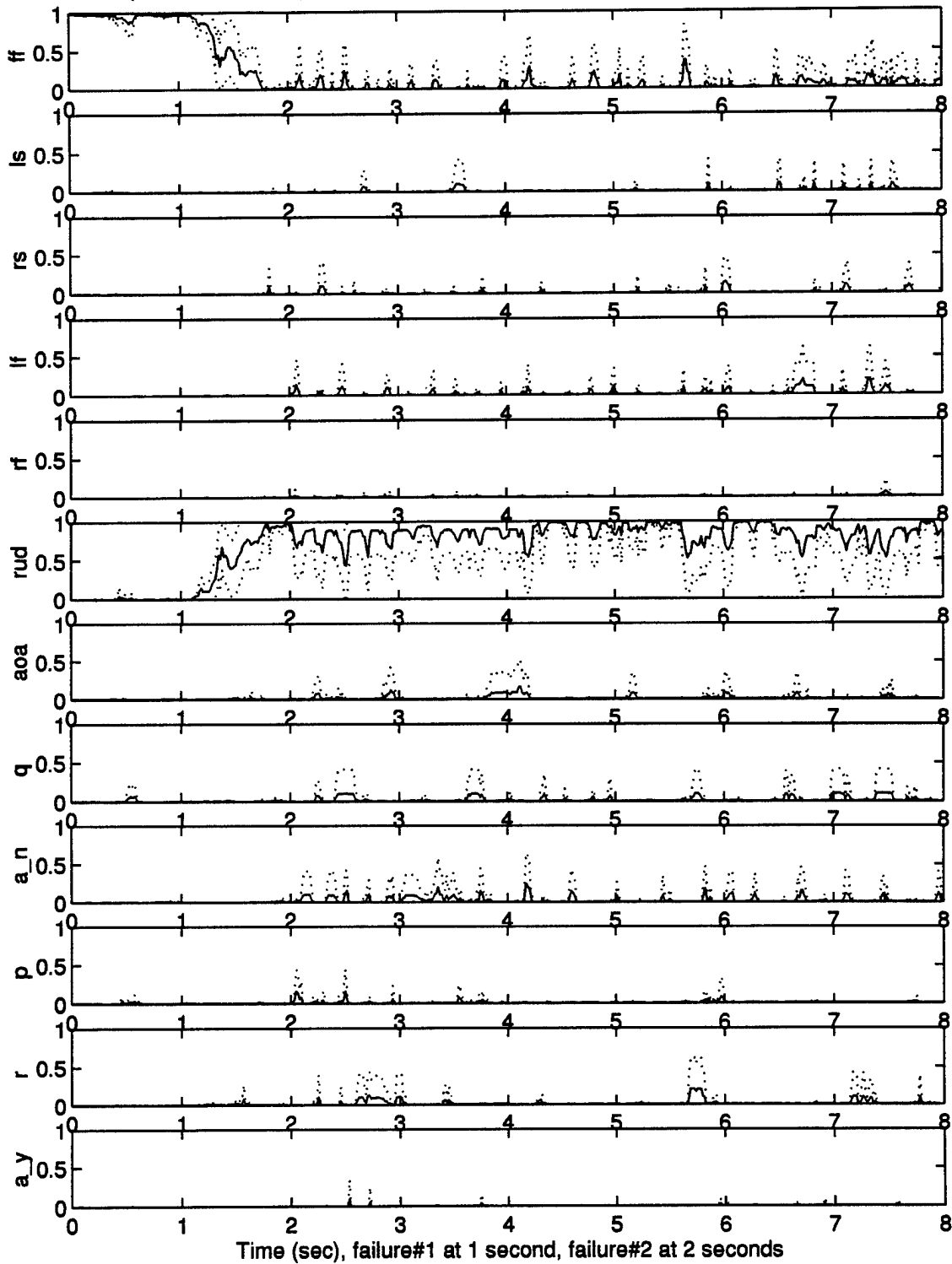
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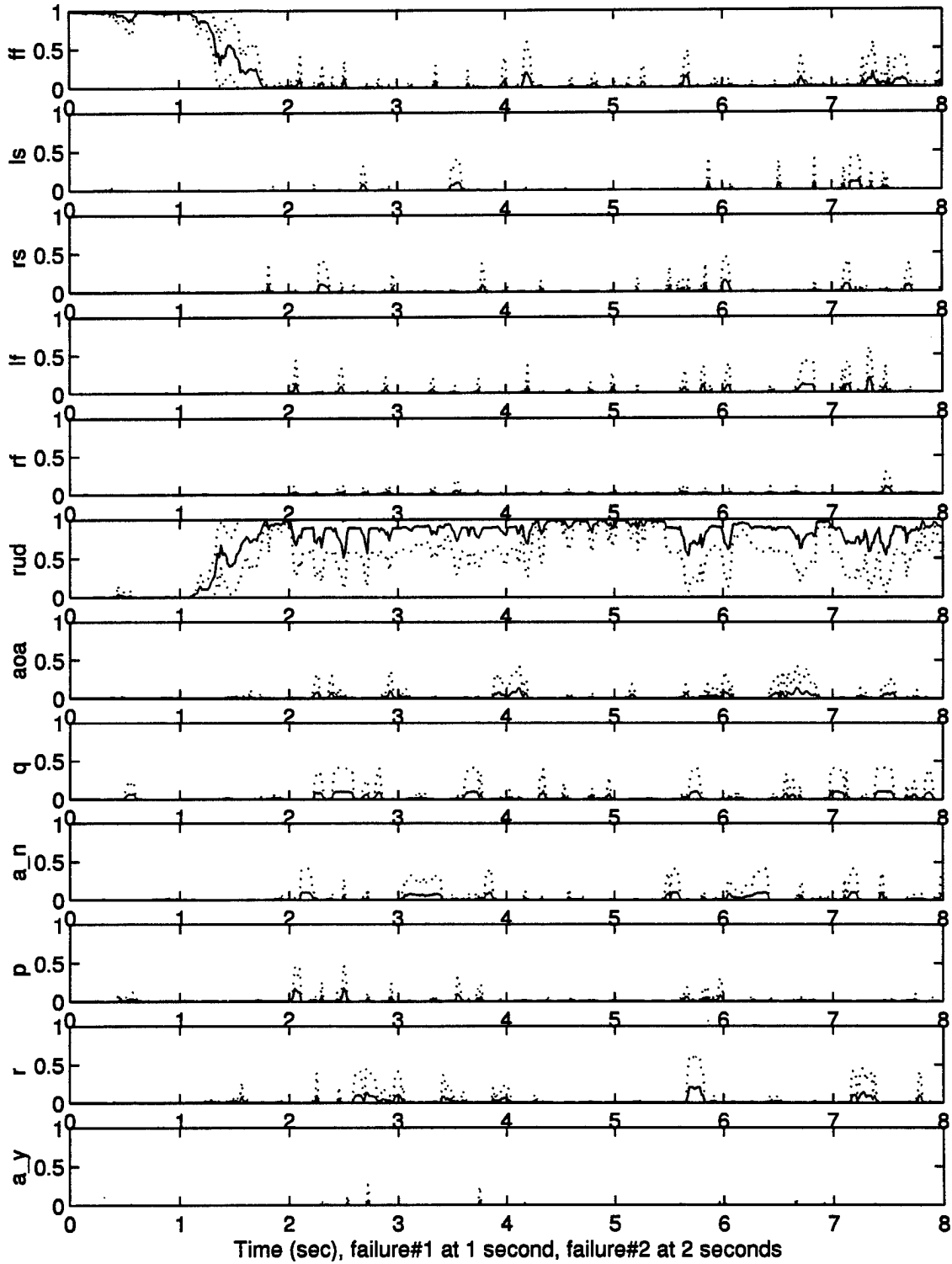
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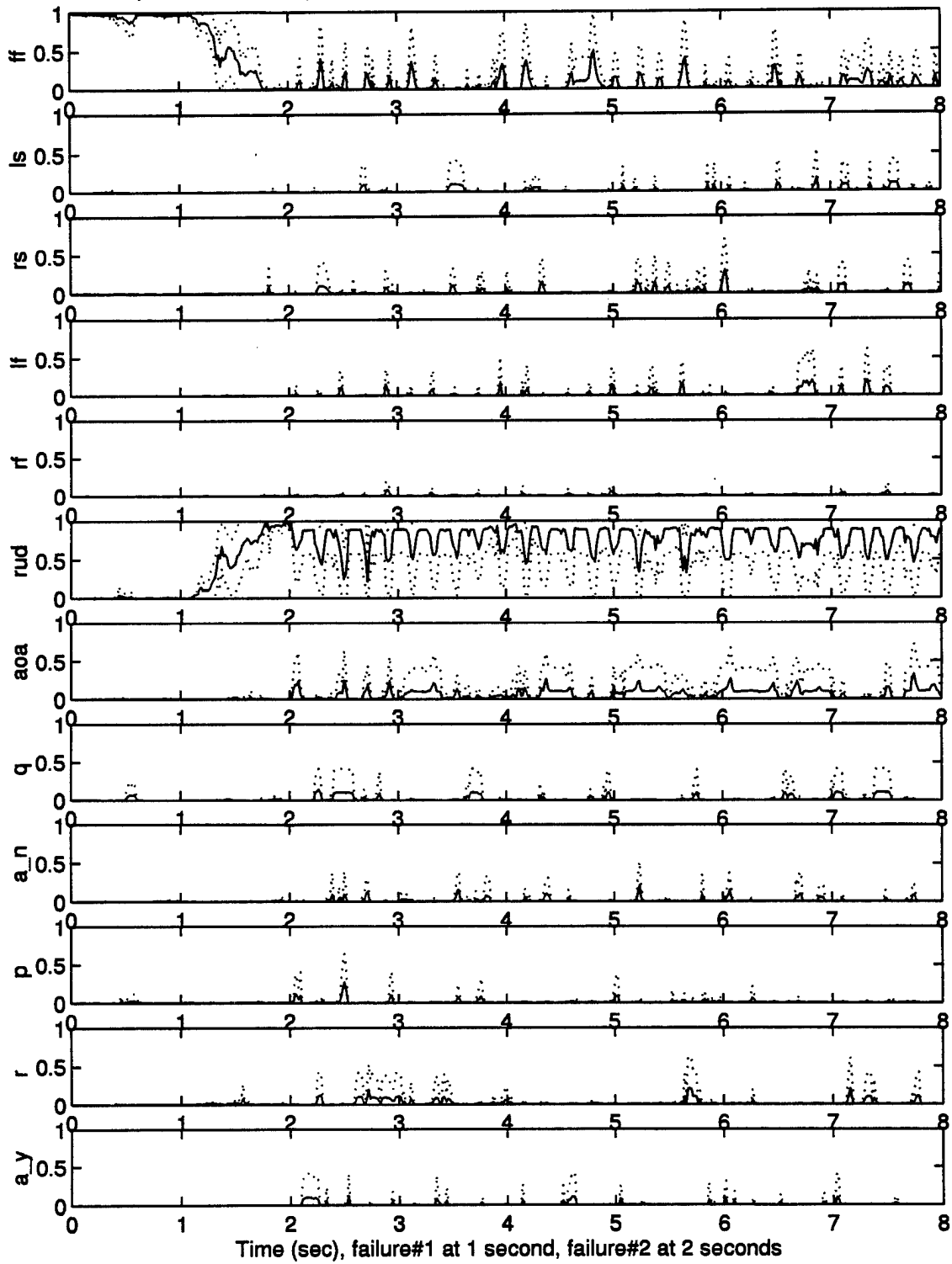
Mean (+/- One Std Dev) Dual-fail Probabilities of fail505.503 with reconfiguration: 10 runs



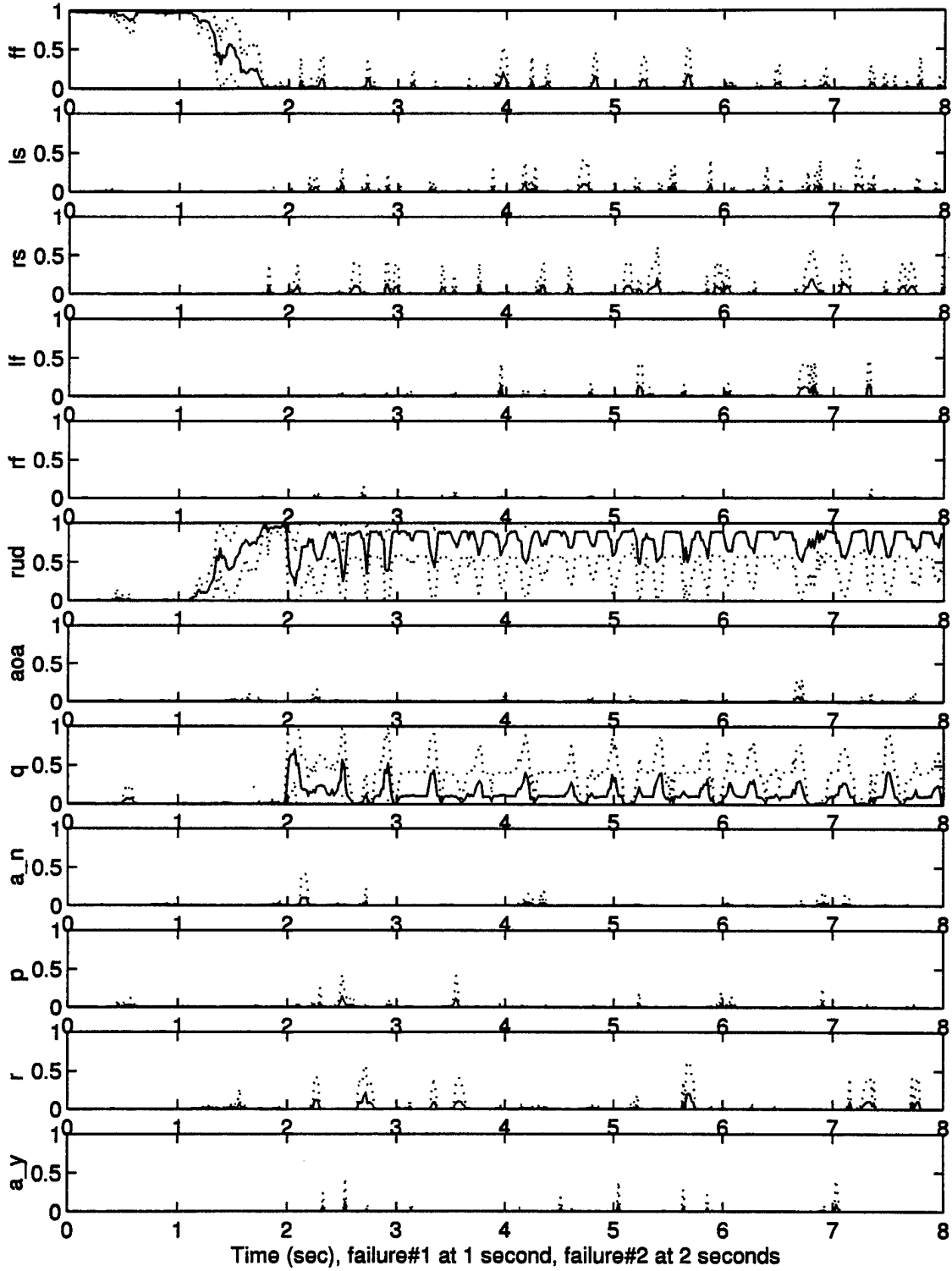
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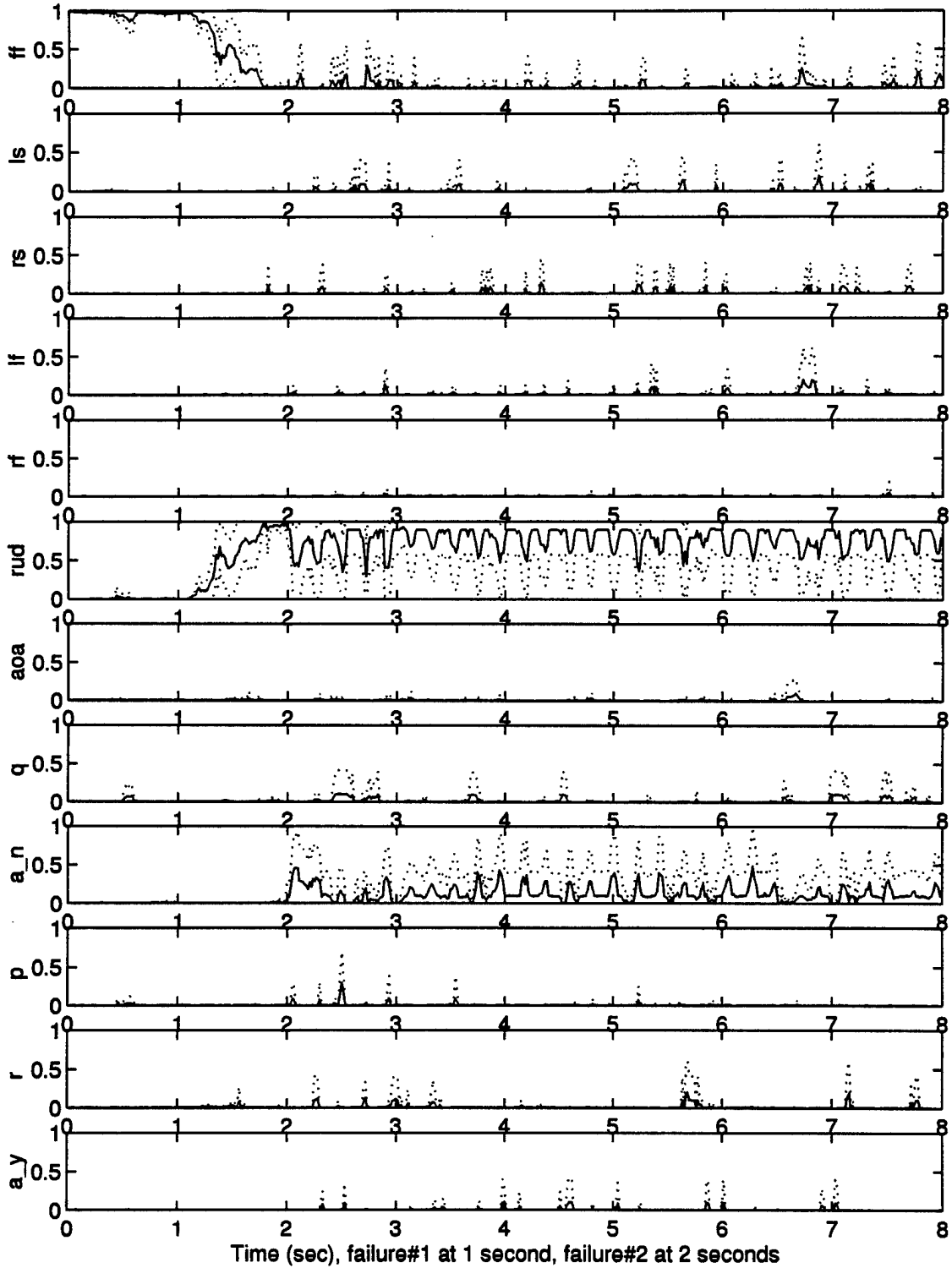
Mean (+/- One Std Dev) Dual-fail Probabilities of fail505.06 with reconfiguration: 10 runs



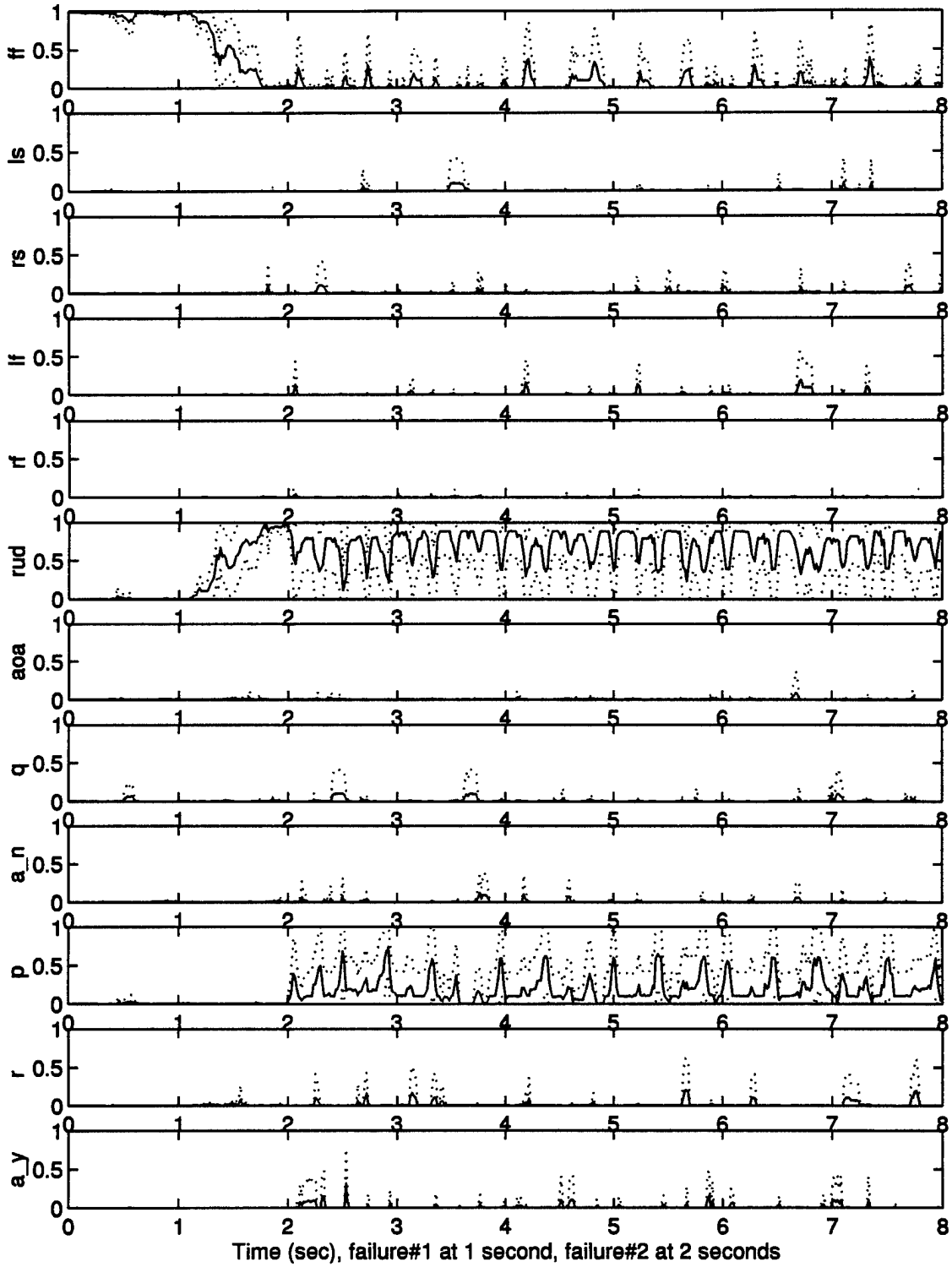
Mean (+/- One Std Dev) Dual-fail Probabilities of fail505.07 with reconfiguration: 10 runs



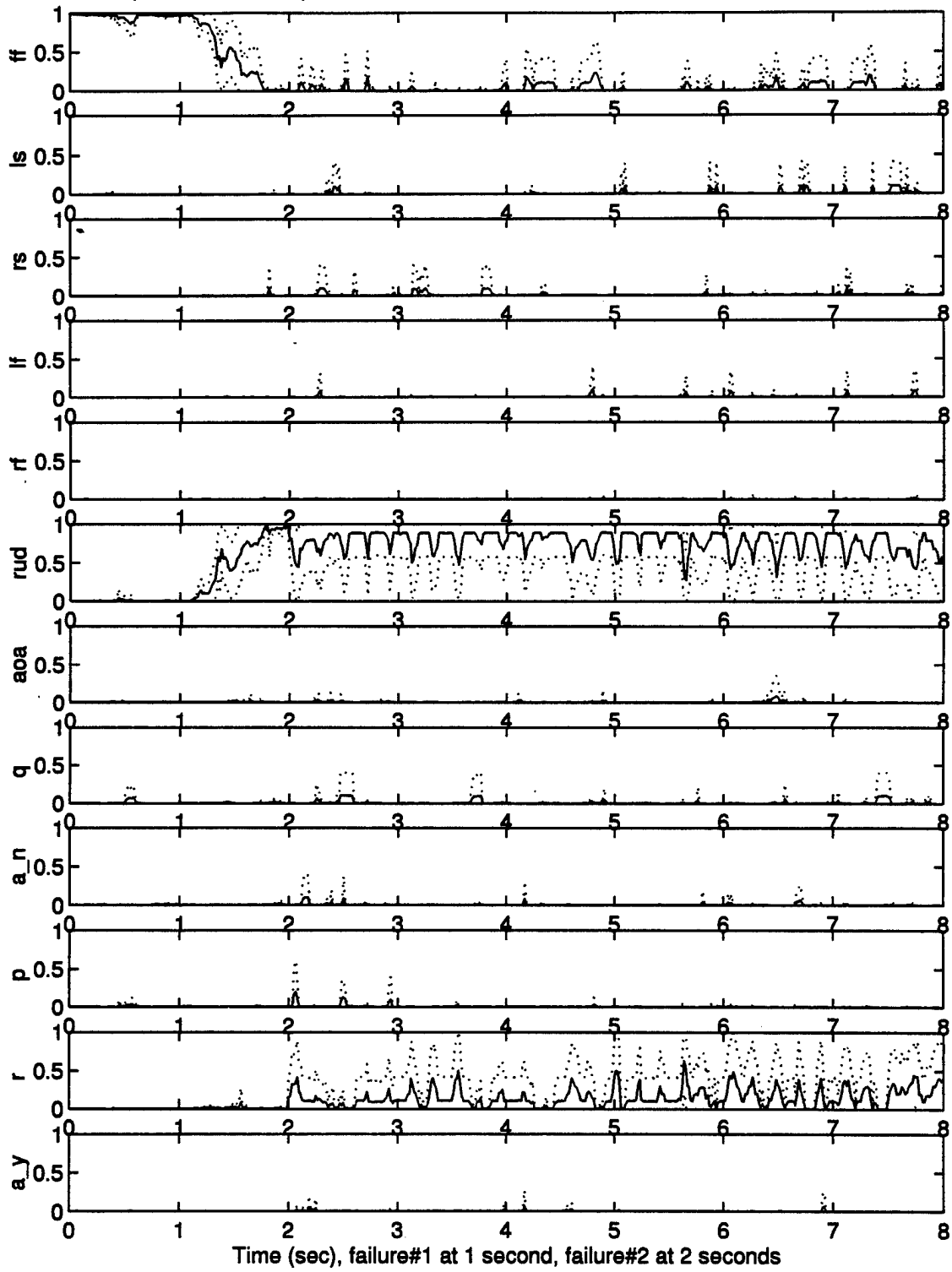
Mean (+/- One Std Dev) Dual-fail Probabilities of fail505.08 with reconfiguration: 10 runs



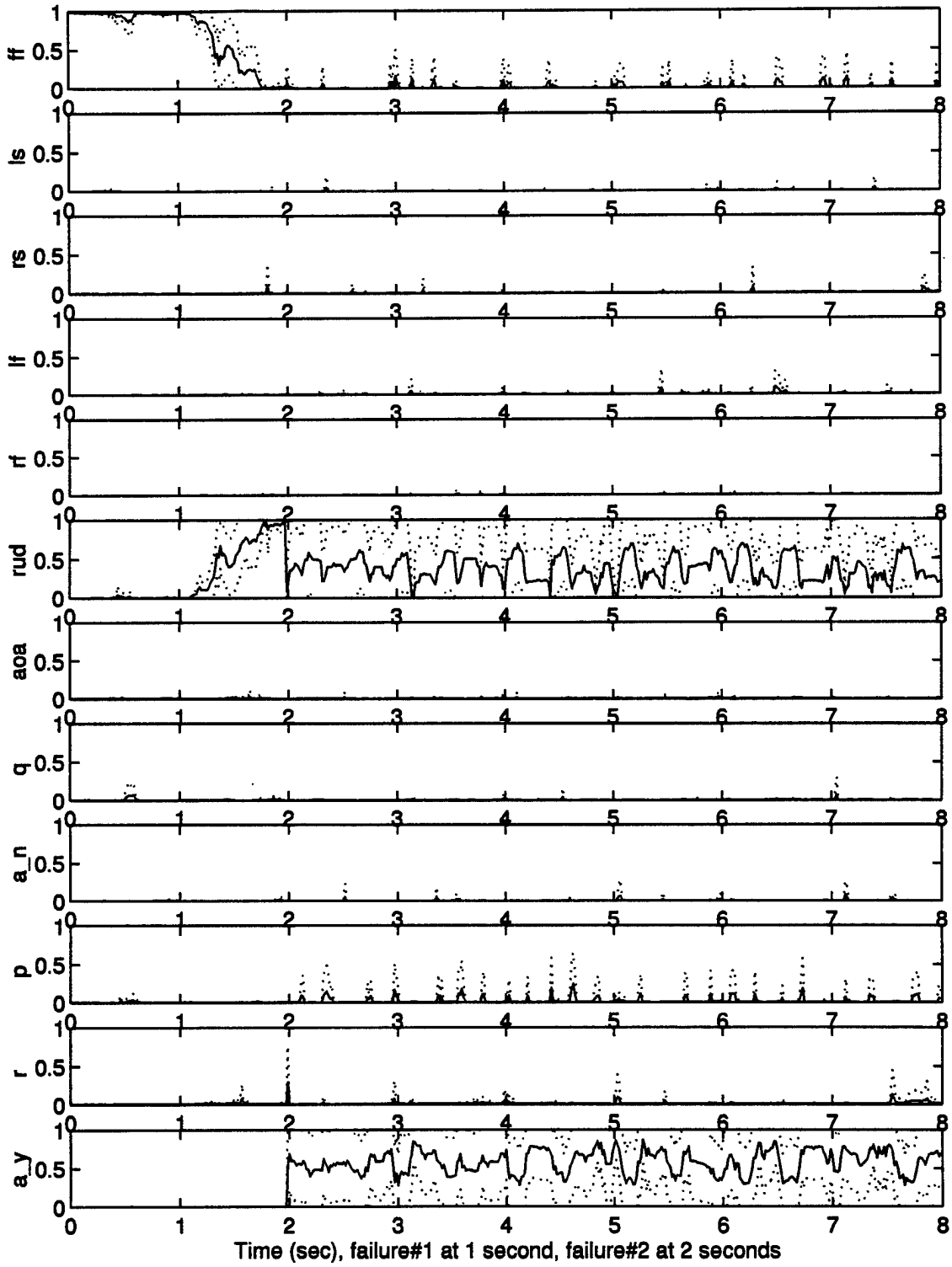
Mean (+/- One Std Dev) Dual-fail Probabilities of fail505.09 with reconfiguration: 10 runs



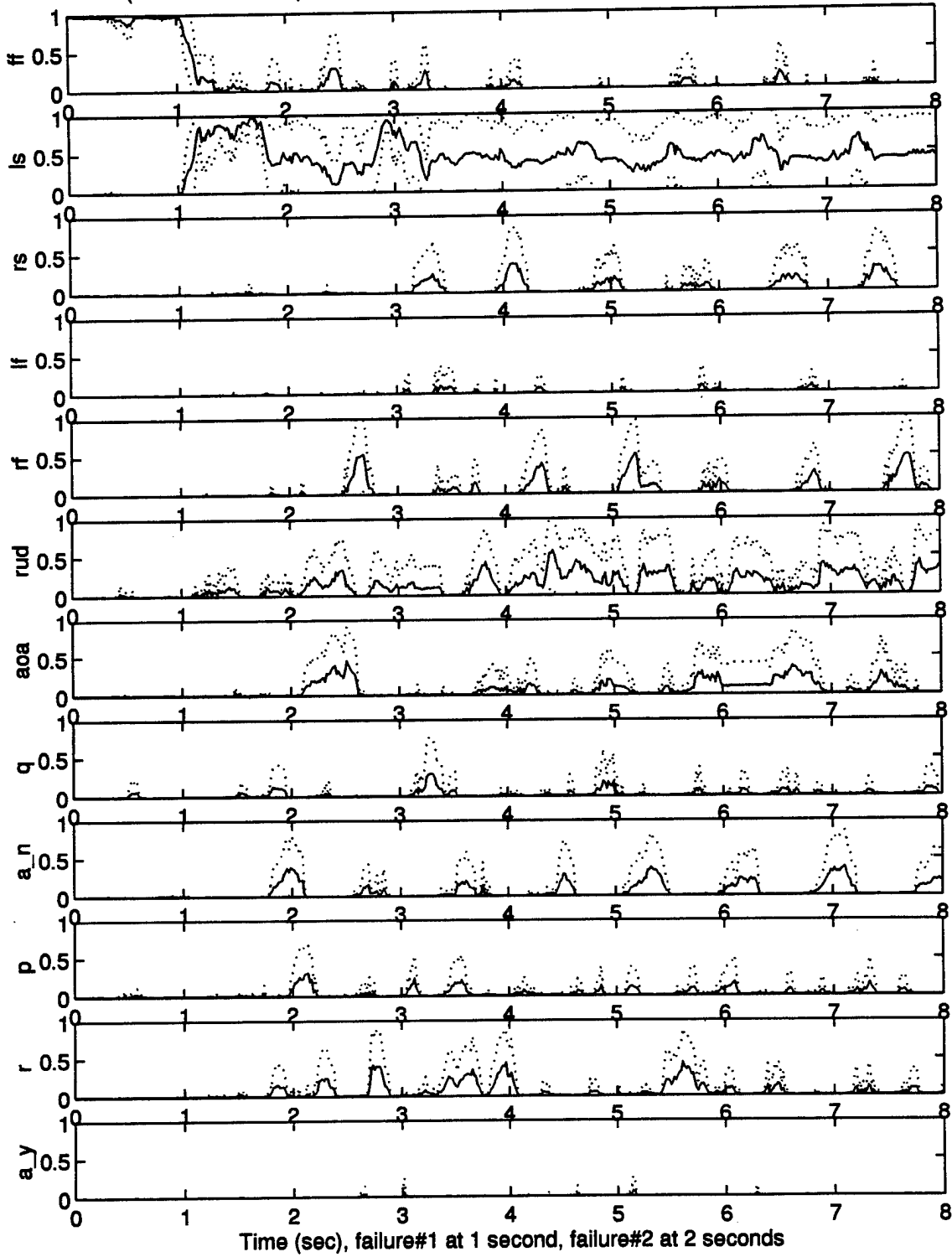
Mean (+/- One Std Dev) Dual-fail Probabilities of fail505.010 with reconfiguration: 10 runs



Mean (+/- One Std Dev) Dual-fail Probabilities of fail505.011 with reconfiguration: 10 runs



Mean (+/- One Std Dev) Dual-fail Probabilities of fail251:250 with reconfiguration: 10 runs



REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE December 1997	3. REPORT TYPE AND DATES COVERED Master's Thesis		
4. TITLE AND SUBTITLE MULTIPLE MODEL ADAPTIVE ESTIMATION AND CONTROL REDISTRIBUTION PERFORMANCE ON THE VISTA F-16 DURING PARTIAL ACTUATOR IMPAIRMENTS			5. FUNDING NUMBERS	
6. AUTHOR(S) Curtis S. Clark GS - 13, D.O.D.				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Institute of Technology, WPAFB OH 45433-6583 Capt. Odell Reynolds WL/FIGS 2210 Eighth St. STE 11 Wright-Patterson AFB, OH 45433-7521			8. PERFORMING ORGANIZATION REPORT NUMBER AFIT/GE/ENG/97D-23	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION AVAILABILITY STATEMENT Approved for public release; Distribution Unlimited			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Multiple Model Adaptive Estimation with Control Reconfiguration (MMAE/CR) capability to estimate and compensate for partial actuator failures, or "impairments" is investigated using the high-fidelity, nonlinear, six-degree-of-freedom, VISTA F-16 simulation which currently resides on the Simulation Rapid-Prototyping Facility (SRF). After developing a model for inserting partial actuator impairments into the VISTA F-16 truth model, research begins with a battery of single actuator impairment tests. This stage of research explores the capability of the existing MMAE algorithm to estimate single, partial actuator impairments, and helps to define refinements and expansions needed in the MMAE algorithm for the second phase of research: the detection and estimation of dual, total and partial actuator impairments. It is seen from the first stage of research that, while MMAE is able to estimate partial impairments, there are refinements needed, such as "probability smoothing and quantization", to compensate for the quality of MMAE probability data and to provide a better, more stable estimate value to the Control Reconfiguration module. The Kalman filters and the dual, partial failure filter banks necessary for the detection of dual, partial actuator impairments are also defined as a result of the single impairment tests. Fifteen more banks of "partial first-failure" Kalman filters are added to the existing MMAE algorithm, as well as the "bank swapping" logic necessary to transition to them. Once the revised and expanded MMAE/CR algorithm is ready, research begins on dual combinations of total and partial actuator impairments. While results of these tests (for other than total impairments) are not as good as originally hoped or expected, the potential for better performance is evident.				
14. SUBJECT TERMS Multiple Model Adaptive Estimation, MMAE, Kalman Filter, F-16, Control Reconfiguration, Flight Control, Failure Detection, Reconfigurable Control			15. NUMBER OF PAGES 400	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	