

CATERPILLAR®

DEMOCRATIZING A MULTIVARIATE STATISTICAL MODEL VALIDATION METHOD THROUGH AN INTELLIGENT FIT-FOR-PURPOSE APP

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COMPANY OVERVIEW

FRONT END ANALYTICS: www.feasol.com



Advanced Analytical Capabilities

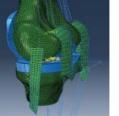
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Intelligent Fit-for-Purpose Apps

Powering Innovation through Simulation Services and Software

Driving Enterprise Impact by Democratizing Experts' Models

Delivering Business Advantage through Detailed Industry Experience



Complex Numerical Modeling Optimization Model Finite Element Model Space Geometry Optimized Design Geometry Shape Optimization Validation Run

Advanced Optimization Technologies



www.feasol.com

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Front End Analytics (FEA) Delivering Business Advantage



COMPANY OVERVIEW INTELLIGENT DEMOCRATIZATION

Intelligent fit-for-purpose applications embed expert knowledge enabling non-expert users the ability to perform complex engineering workflows that traditionally only experts could complete.

Intelligent Apps features include:

- 1) Leverage the company's existing intellectual property (knowhow, methods, toolset, previous designs, etc.)
- Work across a wide range of design changes and product families
- 3) Speak the language of the intended user and prevent non-expert users from creating invalid designs
- 4) Automate an entire workflow (i.e. should work for both CAD creation as well as analysis automation)
- 5) Can be employed for different levels of model abstraction (i.e. from 1D functional-centric to 3D CAD and FEA/CFD computational analysis).



has would it means to a manufacture, if anyone who company sandards, within minutes and with reduced reliance upon the company's experte? What it the product design and simulation knowledge of the engineering experts in your organization could be tapped on-demand through the use of intelligent web-milded "irrutal engine engine engine engine miletigent web-milded "irrutal engine" application?

Imagine how your company's product development processes and go-to-marke strengy would change. Designer could configure products with the assurance that their designs would be engineering validated. Sales resp could engineer products, on the fly, and in front of customers based on their requirements. Junior angineers would be also generate product designs and perform analyses without bogging down your company experts.

Intelligent Automation

Juan Bers, Managing Director of Front End Analysics say, "Back in the enty 1000, adving the infance of the anomowing industry one needed to have deep knowledge of how a car worked in order of rive a car." Today the automotive industry is a 51.5 million industry because, through intelligent automation and controls, someone who has to clut how a car works can drive a car. The engineering design and simulation industry is still in the 1900 requiring the developers of engineering models to be the same persons as the users of these models. In the same way you dorn beed to be a meeting of the engineering engineering expersise or ensue a product eding in the user of meeting of the same transport enable folls who are not experts to use engineering expersise of creates a gradue design through intelligent sucnasions methods. Front End Analytics helps companies runnform how they creates, still and service product via the use of intelligent web-

create, sei and servee product via nie use or intenagent weoenabled Smart Apps. These applications inbed design rules, engineering practices and experts' knowhow, thereby allowing anyone enterprise-wide to safely create a product design. Smart Apps have five major characteristics. They:

- 1 Leverage the company's existing intellectual property (rules, knowhow, previous designs, etc.)
- 2 Work across a wide range of design changes and product families
- 3 Speak the language of the intended user and prevent non-expert users from creating invalid designs
- 4 Automate an entire workflow (i.e. should work for both CAD creation as well as analysis automation)
- 5 Can be employed for different levels of model abstraction (i.e. from 1D functional-centric conceptual design to 3D



parametric CAD and FEA/CFD analysis in detailed design). To create these Smart Apps, From End Analysis lowerages the company's existing IP and usol set (Excel spreadsheets, MATLAB stepin, in-bose code, CAD/CAE took, databases, automation platform. A platform that From End Analysics forties uses it called EASA, a code accompating platform for rapid application development, process sutomation and enterprisewide software accessibility.

These Smart Apps can be safely tucked away behind a company's firewall or accessible through the web. Different Apps or functionalities within Apps can be made available via user permissions following each company's IT policies.

The Process

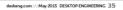
Front End Analytics works closely with companies to assess their workflows, engineering challenges, design practices, expert knowhow, etc. to diagnose the best course of action that would lead to desired outcomes. "We always diagnose before we prescribe," asys Betts.

"We meet with companies as a neutral third party, saying focused on the faces as part of our education. Extracting the deterministic rule sets needed for the automation leads to their own discoveries about what they did and did not know," says Mark Walker from Front End Analytics. "In the end, it's their consensus that makes the solution successful."

Once a company's core design process and engineering rules are codified, various applications can be created to help streamline product evelopment. "We make the application speak the language of the intended users across the enterprise and add intelligent controls to prevent non-expert users from creating an invalid product design," Waller says.

Many companies begin with a small pilot and then scale up. For more info on how Front End Analytics can help auto mate your engineering workflow, visit www.feasol.com.

Front End Analytics (FEA)







AGENDA

METHODOLOGY

VALIDATION

DEMOCRATIZATION

CONCLUSIONS







AGENDA

METHODOLOGY

VALIDATION

DEMOCRATIZATION

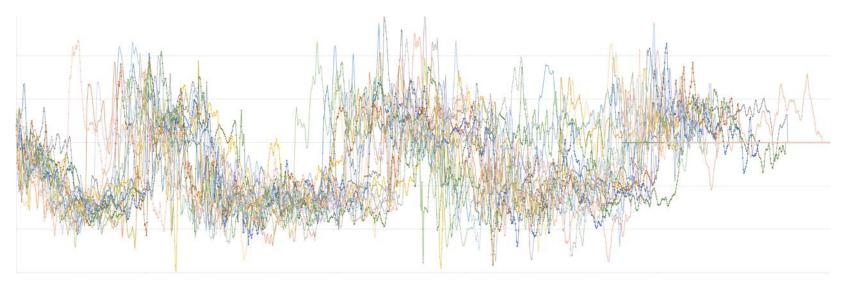
CONCLUSIONS





METHODOLOGY

ARE WE FROM THE SAME FAMILY?







Front End Analytics (FEA) Delivering Business Advantage

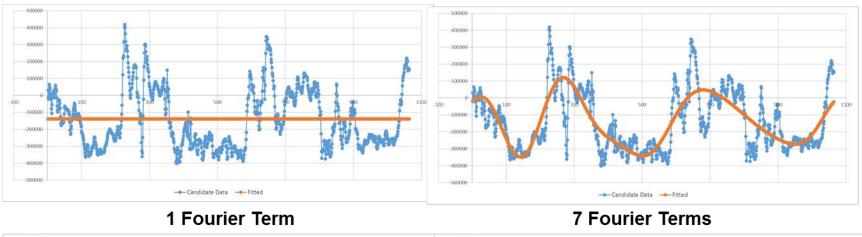


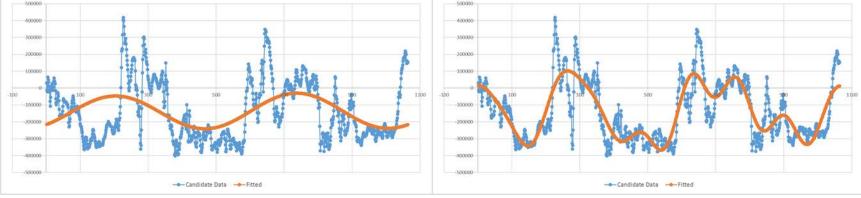




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METHODOLOGY FOURIER SERIES UNCOVERS SHAPE





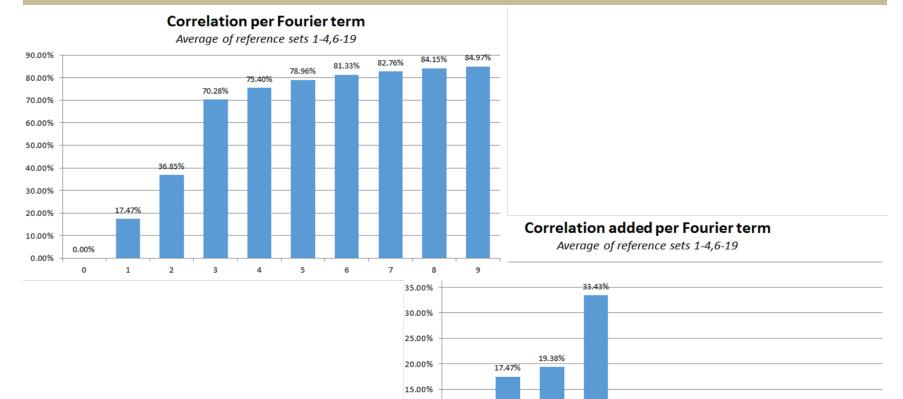
3 Fourier Terms

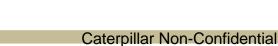
10 Fourier Terms





METHODOLOGY TIME SERIES CORRELATION OF FOURIER SERIES





10.00%

5.00%

0.00%

0.00%

0

2

1

3

1.40%

8

0.82%

9

1.42%

7

5.12%

4

3.55%

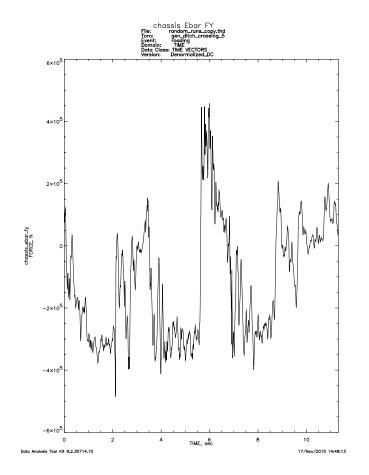
5

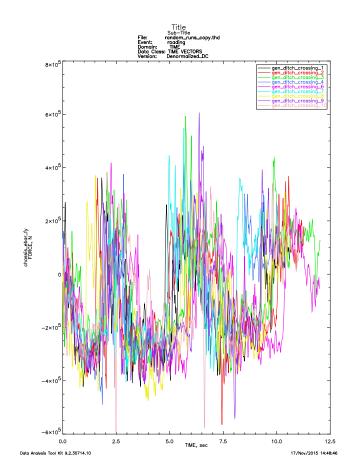
2.38%

6



METHODOLOGY WEAK TEST – ONE VS. MANY









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Vs.

METHODOLOGY WEAK TEST – EQUIVALENCE OF MEAN

A. Compute Fourier Coefficients (Candidate/Reference)

$$x_{ri}(t) = \frac{a_{r0i}}{2} + \sum_{n=1}^{N} \left[a_{rni} \cos\left(\frac{2\pi nt}{T_{ri}}\right) + b_{rni} \sin\left(\frac{2\pi nt}{T_{ri}}\right)\right]$$

- B. Compute means and standard deviations
- C. Compute reference covariance matrix
- D. Invert reference covariance matrix
- E. Assess Hotelling's T² distribution

 $(\mathbf{y}_{cand} - \bar{\mathbf{y}}_{ref})^{\mathrm{T}} \mathbf{S}_{ref}^{-1} (\mathbf{y}_{cand} - \bar{\mathbf{y}}_{ref}) \sim T_{p,n_{ref}-1}^{2}$

F. Map to F distribution

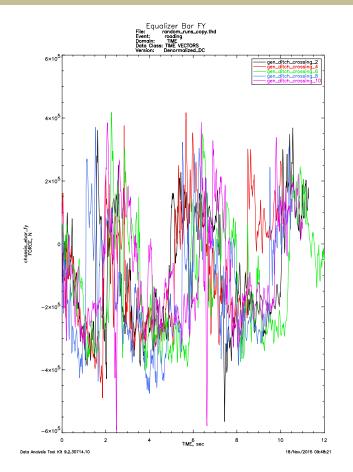
$$\frac{(n_{\rm ref}-p)}{p(n_{\rm ref}-1)}T_{p,n_{\rm ref}-1}^2 \sim F_{p,n_{\rm ref}-p}$$

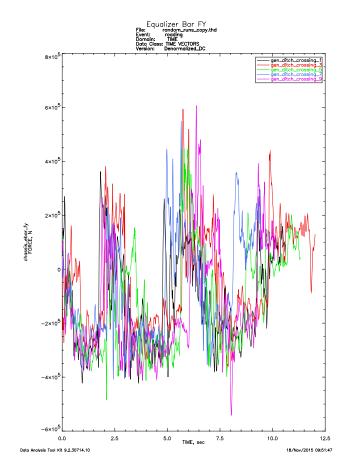
G. Get P-value of F distribution





METHODOLOGY STRONG TEST – MANY VS. MANY









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VS

METHODOLOGY STRONG TEST- EQUIVALENCE OF MEAN

- A. Same as A & B in Weak Test
- B. Compute pooled covariance matrix

$$\mathbf{S}_{\text{pl}} = \frac{1}{n_{\text{ref}} + n_{\text{cand}}} \left[(n_{\text{ref}} - 1)\mathbf{S}_{\text{ref}} + (n_{\text{cand}} - 1)\mathbf{S}_{\text{cand}} \right]$$

- C. Invert pooled covariance matrix
- D. Assess Hotelling's T² distribution

$$(\bar{\mathbf{y}}_{cand} - \bar{\mathbf{y}}_{ref})^{\mathrm{T}} \left[\left(\frac{1}{n_{ref}} + \frac{1}{n_{cand}} \right) \mathbf{S}_{pl} \right]^{-1} (\bar{\mathbf{y}}_{cand} - \bar{\mathbf{y}}_{ref}) \sim T_{p,n_{ref}+n_{cand}-2}^{2}$$

E. Map to F distribution

$$\frac{n_{\rm ref} + n_{\rm cand} - p - 1}{(n_{\rm ref} + n_{\rm cand} - 2)p} T^2 = F_{p,n_{\rm ref} + n_{\rm cand} - p - 1}$$

F. Get P-value of F distribution



METHODOLOGY

STRONG TEST- EQUIVALENCE OF VARIANCE

A. Calculate M-statistic for M-test

$$M = \frac{|\mathbf{S}_{\rm ref}|^{(n_{\rm ref}-1)/2} |\mathbf{S}_{\rm cand}|^{(n_{\rm cand}-1)/2}}{|\mathbf{S}_{\rm pl}|^{(n_{\rm ref}+n_{\rm cand}-2)/2}}$$

B. Calculate c1 coefficient

$$c_1 = \left[\frac{1}{n_{\text{ref}} - 1} + \frac{1}{n_{\text{cand}} - 1} - \frac{1}{n_{\text{cand}} + n_{\text{ref}} - 2}\right] \frac{2p^2 + 3p - 1}{6(p+1)}$$

C. Calculate u for p-value lookup

 $u = -2(1 - c_1)\ln(M) \sim \chi^2 \left[p(p+1)/2 \right]$

D. Get P-value from Chi-squared distribution







AGENDA

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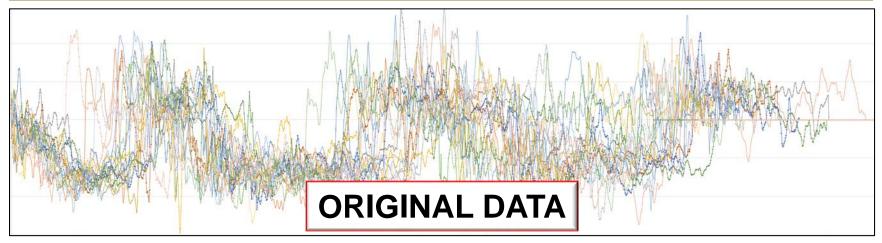




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STATISTICAL MODEL VALIDATION

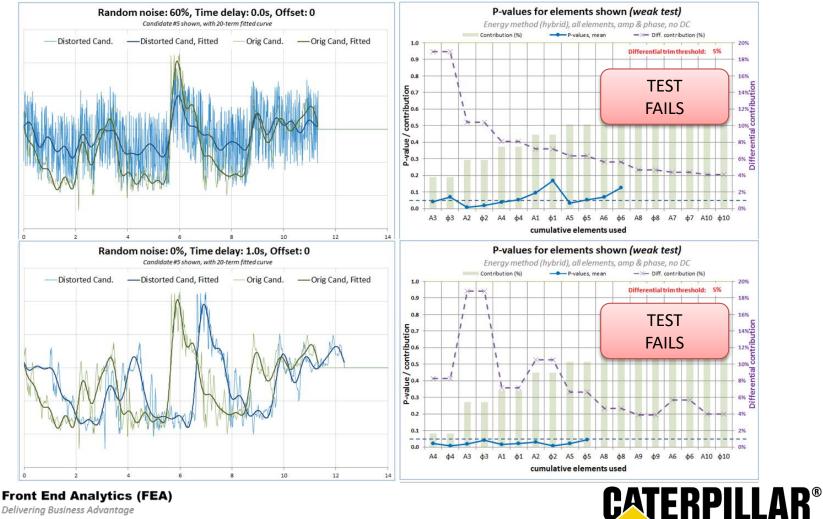
SEE IF TEST PASSES ON KNOWN DATA





DFI IVERING BUSINESS ADVANTAGE

STATISTICAL MODEL VALIDATION **ADDING 60% NOISE AND SHIFTING CANDIDATE SIGNAL BY 1S**

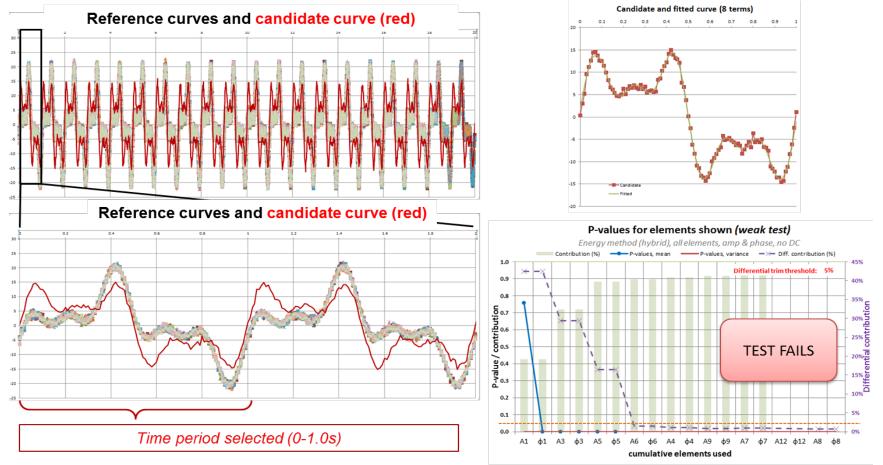


Deliverina Business Advantaae



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STATISTICAL MODEL VALIDATION MORE COMPLEX CASES



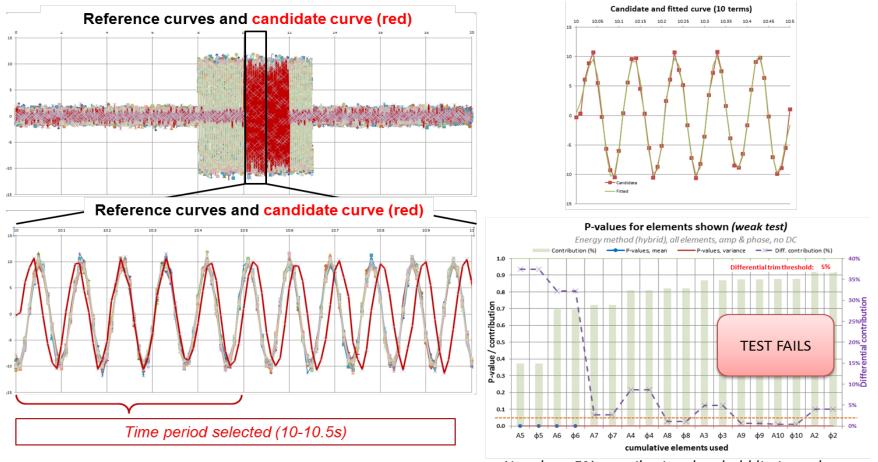
Note how 5% contribution threshold limits p-chart

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STATISTICAL MODEL VALIDATION MORE COMPLEX CASES

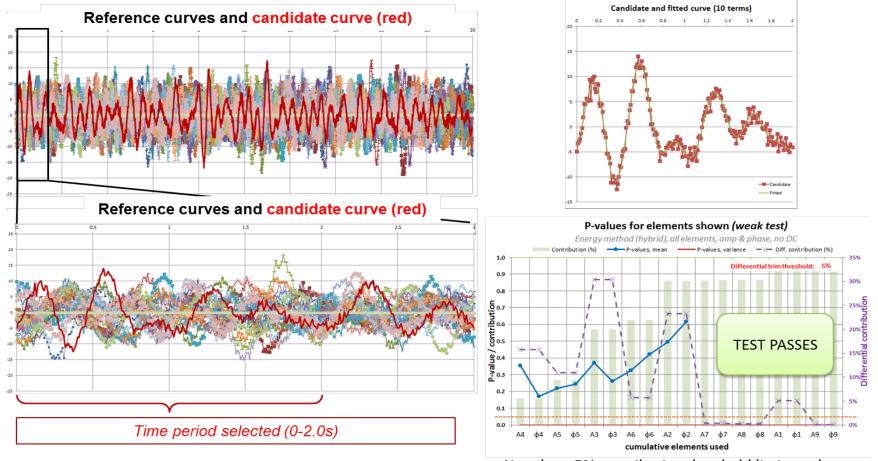


Note how 5% contribution threshold limits p-chart

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STATISTICAL MODEL VALIDATION MORE COMPLEX CASES



Note how 5% contribution threshold limits p-chart

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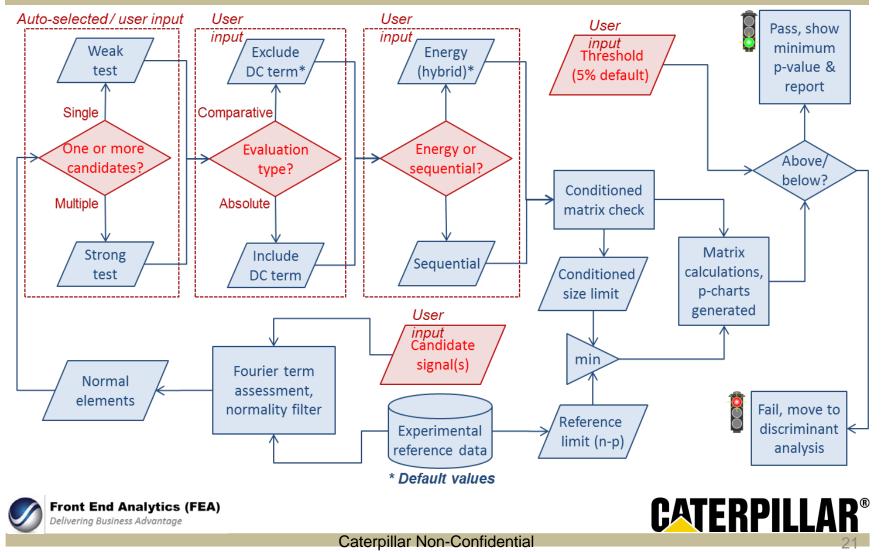
CONCLUSIONS





DEMOCRATIZATION

WORKFLOW



DEMOCRATIZATION SAMPLE GUI (1/2)

Statistical Model Validion × C Second Secon	• • • • ×	\bigtriangledown	added here fo	r testing, re	ified, distortion is ference sets are parameters are set
Bandom noise:0%, Time delay: 1.05, Offset: 0 Endotre 0 Journ - 49, 35 excitator or Distorted Cand, — Distorted Cand, Fitted Distorted Cand, Mitted Distorted Cand, Pitted Distorted Cand, Pitted	Add another source	12uid=D229C1CBE	· · · · · · · · · · · · · · · · · · ·		i parameters are set
· · · · · · · · · · · · · · · · · · ·		Test settings Event type: Include DC term?: Test strength: Threshold (%):	Cycle Non-cycle Yes No Low Medium High S	NAME OF TAXABLE AND A DESCRIPTION	uideD229C1CBE0364CEF6001F879A3F7Ft☆ ☐ □ = el Validation
	- A CALANA A A A A A A A A A A A A A A A A A	— Note Candidate(a) in re	d shown overtaid on reference signals	n (weak test) mp & phaze, no DC 	Test Metrics Test type: Weak Event type: Weak D0 included: No Test strength: Low Failure threshold: 5%
on top of the o	<u>1sec delay</u> signal distortion candidate <u>IS NOT</u> a believable er of this reference set		100 100 100 100 100 100 100 100	45 40 60 A5 66 A50 610 45 40 60 A5 66 A50 610 45 40 60 A5 66 A50 610	Evaluation metrics Minimum p-value: 0.0074 Elements used: 8 Highest energy: A4 Conclusion The simulated candidate curve IS NOT a member of the reference population





DEMOCRATIZATION SAMPLE GUI (2/2)

Statistical Model Validation × ← → C Discalhost/jsf-easa/prefsc.easapjsessionid=redirect SFEA Statistical Model Simulated candidate(s) Defenses entrol Destruction	el Validation		added here fo	r testing, re	ified, distortion is ference sets are parameters are set
Random noise: 2005, Time delay: 0.05, Offset: 0 Groadware Alawa and Shawmanawa — Disorted Cand, — Disorted Cand, Fitted — Disorted Cand, — Disorted Cand, Fitted	Candidate file(s) Source file: Add another source			•	
Mar Martin	Additional signal distortion Random noise (%) 50 Time delay (sec) 0 Update	I=redirect?uid=D229C1CBE Model Valida			
	Tiers times	Test settings Event type: Include DC term?: Test strength:	Cycle O Non-cycle Ves No Low Medium O High		🔳 - o 🎫
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	i a lookeen i kuitu	Note: Candidate(s) in re	d shown overlaid on reference signals	n (weak test) Imp & phase, no DC 	Test Metrics Test type: Weak Event type: Weak DC includer No Test strength: Low Fakre threshift: 5%
	<u>30% noise</u> signal distortion e candidate <u>IS</u> a believable			2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2	Evaluation metrics Minimum p-value: 0.3066 Elitenets used: 10 Highest energy: A3
membe		0.1 0.0 A3 0.5 A2 0.2 A4 0.4 A3 0.5 A5 0.5 A6 5% Product thereford	φ6 Αδ φ3 Α7 φ7 Αθ φα	Conclusion The simulated candidate curve IS a member of the reference population	







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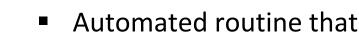




CONCLUSIONS

SUMMARY

- Manual time histories alignment no longer necessary
- Consistent and userindependent results are obtained
- Greater method adoption due to streamlined workflow and embedded expert knowledge in the tool.
- Use of multivariate statistical approach reduces exposure to Type I and II error
- Power of the hypothesis test can be "tuned" to the specific problem being validated



FUTURE WORK

- automatically improves numerical models to pass hypothesis testing validation
- Other multivariate problems: e.g. inverse problem, load uncertainty, predictive maintenance, loT, etc.









QUESTIONS?







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