An Assessment of an FEA Body Model for Design Capability

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Finite Element Analysis (FEA) models are routinely being adopted for up-front automotive body structure design. FEA models serve two important functions: first, to assess a design versus an absolute target; second, to assess the performance of various design alternatives. Means of assessing model capability are required to feed appropriate information into the design process. Being able to document model capability improves the credibility of the FEA model information. Previous work addressed assessing the absolute performance of model technology using a metric based on a statistical hypotheses test that determines membership in a reference set. This article extends the use of quality technology to determining the capability of the FEA model to span the design space using Designed Experiments. The advantage of a design of experiments (DOE) structure is that both the design effects and their statistical significance are uncovered.

Computer Aided Engineering (CAE) has been replacing prototype testing in the automotive industry on a very large scale, due to ever-increasing prototype costs and time to market pressures. Indeed, the prohibitive prototype costs found in the aerospace industry have already led to it adopting a more CAE-based design philosophy. As with any industrial process, the issues of quality control and continuous improvement must be addressed, typically through some form of monitoring or process control. Unfortunately, this has not always been the case for CAE predictions.

A Quality Operating System (QOS) in accordance with ISO9001 should be developed to control and improve the CAE environment. One such attempt is suggested by NAFEMS,[1] but the idea of CAE quality is not unique to them. An important aspect of a QOS is being able to objectively evaluate the predictive performance of the analysis.

An objective metric to assess the baseline capability of CAE models was developed in Reference 2. The metric is capable of determining the probability that a CAE model is representative of test data based on a comparison of frequency response functions. This is accomplished by developing a statistic d based on the differences between the CAE model and test frequency response functions (FRFs). The metric d/s is a statistic where d represents the summation of the squared differences between a test article (or CAE prediction) and a reference set average at each frequency band, across all FRFs, as well as across all articles in the reference set while s represents the standard deviation at each frequency band pooled across all FRFs and test articles in the reference set. Consequently, d/s values less than or close to 1 indicate "no difference" between the test article (or CAE prediction) and the reference set. Under certain assumptions d/s is chi-squared distributed and the probability of the CAE model being representative of the test model can be ascertained.

In this article, the ability of FEA predictions to span the design space is evaluated by comparing a hardware-designed experiment (DOE) to predicted results. This technique was initially proposed to evaluate statistical energy analysis (SEA) model predictions.[3-5] This article explores the predictive capability of a FEA body model for both a BIW (Body-In-White) with fixed glass and a trimmed body model.

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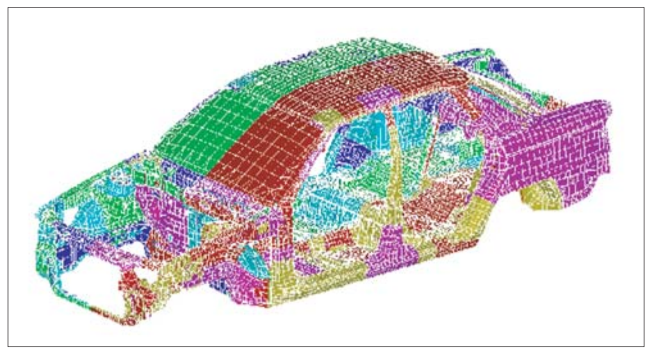

Figure 1. BIW with fixed glass hardware and finite element model representation.

BIW with Fixed Glass Model

A BIW with fixed glass FEA model was built with 150,000 elements/grids and 3500 spot welds. The spot welds were modeled with a RBE2 spider that simulated their contact area, assumed at 70 mm^2 for this study. Both modal analysis and quality metrics were applied to evaluate the model, which is shown in Figure 1. The body modal performance is shown in Table 1.

The CAE vs. test FRF comparisons using NVH CAE quality metrics resulted in a baseline model performance index of 1.62.[2] The analysis was performed using a standard deviation of 2.80 dB determined from a separate midsize car BIW variability study. The analysis was performed using 1/12 octave band data, resulting in 44 frequency bands and 56 frequency response functions (FRFs) from 20 to 250 Hz. The reported power value is 0.95, a level which does not recognize the test

Table 1. FEA model modal performance.

Mode	Test	Analysis	%Error
Overall Torsion	31.9	32.7	2.5
Front Lateral Bending	35.8	37.0	3.3
First Bending	40.2	41.0	1.9
Second Bending	44.2	45.0	1.8
Center Floor Bending	47.2	47.7	1.0

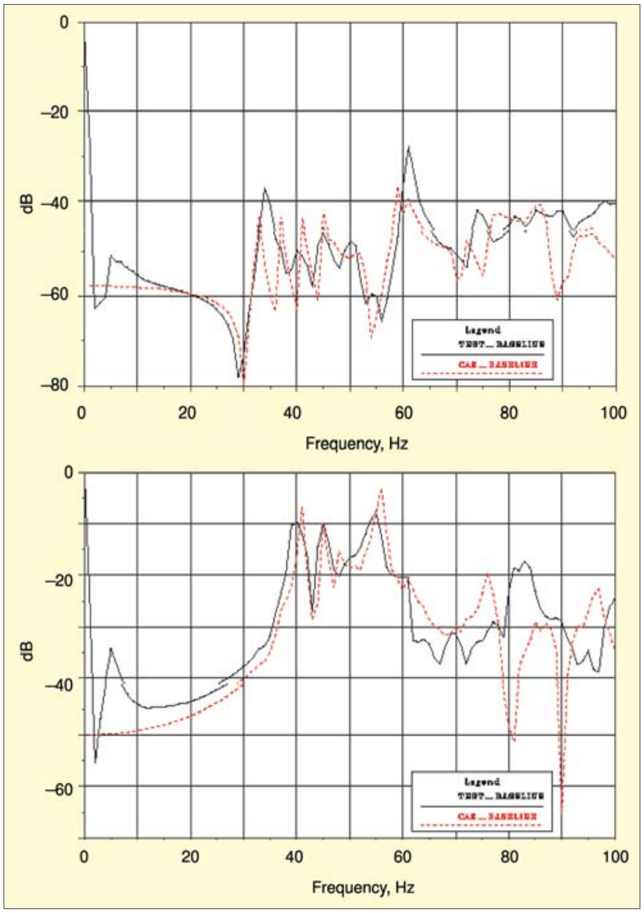

Figure 2. Sample frequency response functions, 0 - 100 Hz.

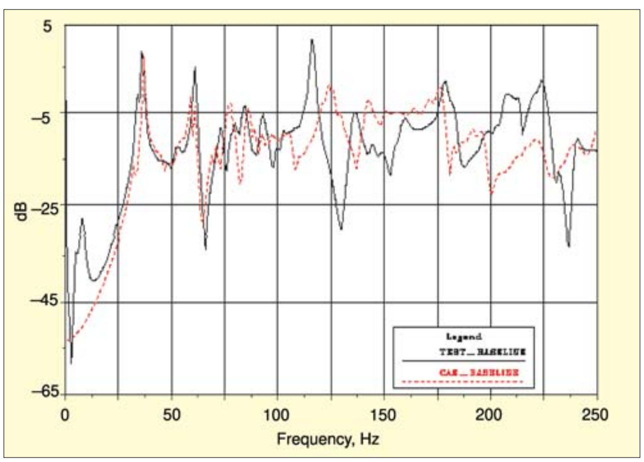

Figure 2a. Sample frequency response function, 0 - 250 Hz.

results as a member of the test set. Sample FRFs are shown for both 0-100 Hz performance and 0-250 Hz performance in Figure 2.

Table 2. Test matrix (0 indicates the modification was not included and 1 indicates the modification was included.

	A	B	C	D	E
Baseline	0	0	0	0	0
Run 2	0	0	0	1	1
Run 3	1	0	0	0	0
Run 4	0	1	0	0	1
Run 5	1	1	0	1	0
Run 6	0	0	1	1	0
Run 7	1	0	1	0	1
Run 8	0	1	1	0	0
Run 9	1	1	1	1	1

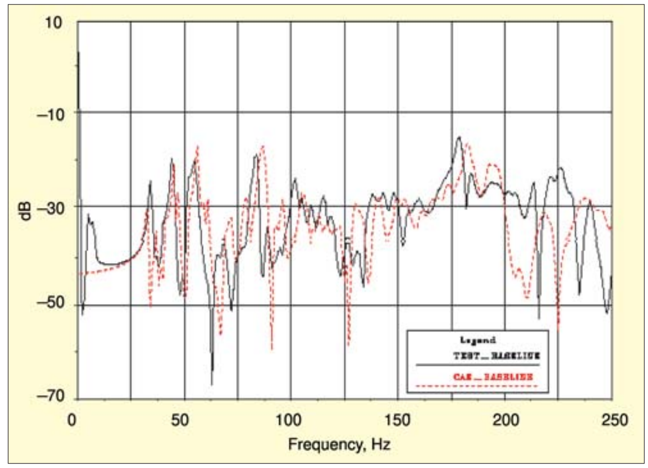

Figure 2b. Sample frequency response function, 0 - 250 Hz.

Figure 3. A – quad box to rail support, B – tunnel strap, C – floor to roof pole, D – rear shocks to rear floor support, E – front shock to radiator support.

Body-In-Prime DOE Study

In a brainstorming meeting, five design changes were selected to implement a DOE to assess the design space. Factor A was a quad box to rail reinforcement, Factor B was a tunnel strap, Factor C was a floor to roof pole, Factor D was an inverted V support between the rear shock towers and the rear floor, and Factor E was a front shock to radiator support. The five hardware changes are shown in Figure 3, while the test matrix for the hardware DOE is shown in Table 2.

Two drive points and 28 response points were selected for

Table 3. Metric scores for run configurations.

	Test	CAE
Run 2	2.37	2.24
Run 3	0.00	0.00
Run 4	1.47	1.31
Run 5	1.66	1.85
Run 6	1.64	1.89
Run 7	1.69	1.44
Run 8	0.00	0.00
Run 9	2.43	2.32

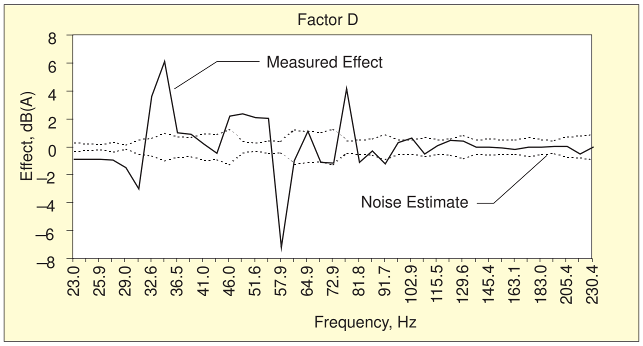

Figure 4. Factor effect for inverted V compared to noise estimate vs. frequency.

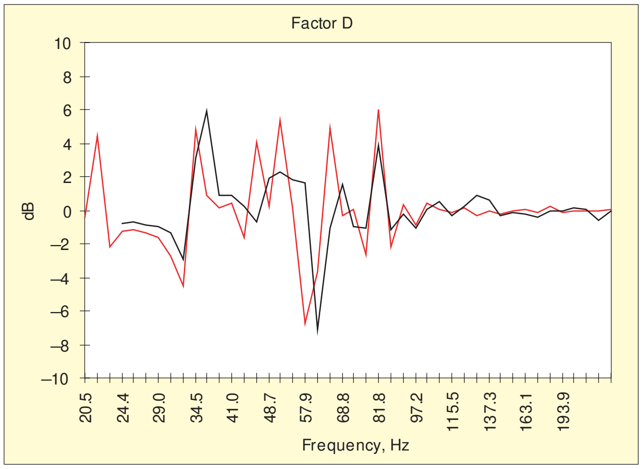

Figure 5. Effects plot for CAE and test for inverted V brace.

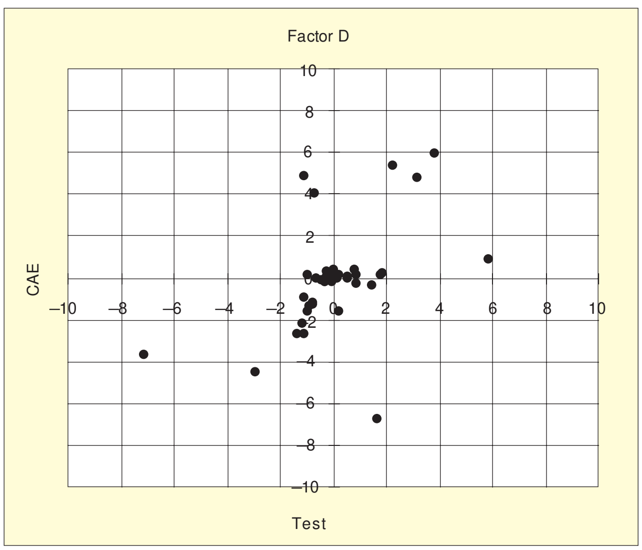

Figure 6. Cross plot of test and CAE effects for inverted V.

the experiment. Frequency responses were measured and predicted for these points, and the points were distributed throughout the body in prime. The drive points were on the front rail laterally and the rear rail vertically. Because of excessively high noise estimates in the physical experiment, the experiment was folded over resulting in a 16 trial experiment.

The data were processed with the NVH CAE quality metrics to determine if the hardware changes resulted in statistically significant changes to the vehicle. The results are shown in Table 3. The test and CAE results for each run were compared to the test and CAE baseline runs respectively. CAE successfully predicted the level of change compared to the baseline in each case.

The data were then processed to determine the factor effects for each of the drive points and the corresponding noise estimates using Lenth's method, with a typical result shown in Figure 4. The red line shows the factor effect and the dashed lines represent the noise estimate at the 80% level of statistical significance. An effect that falls inside the dashed line could be due to mere chance variation.

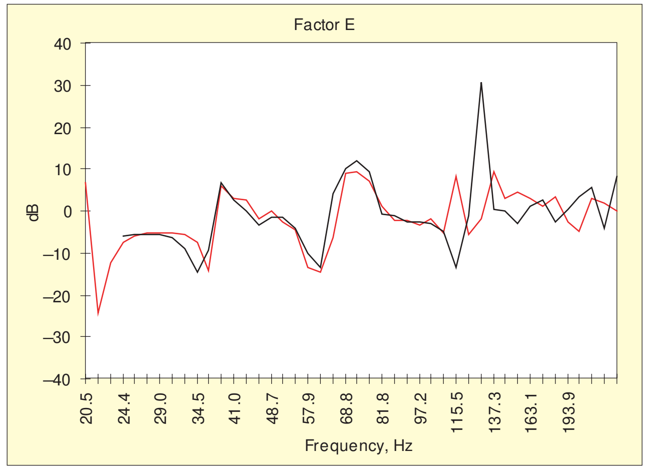

Figure 7. Factor effect comparison for K brace.

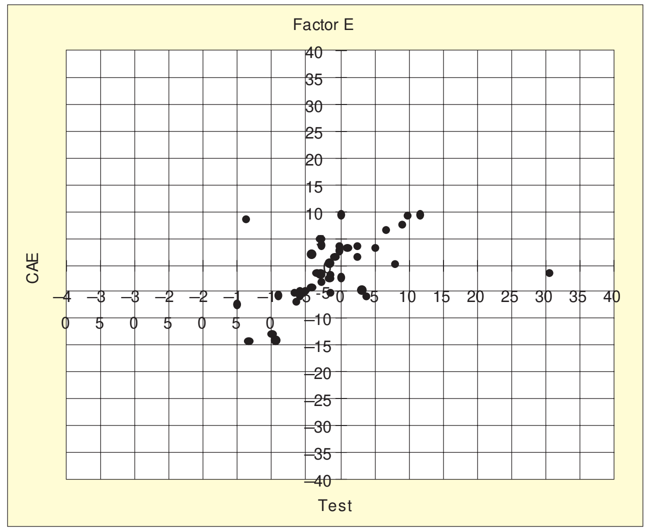

Figure 8. Factor effect cross plot for front K brace.

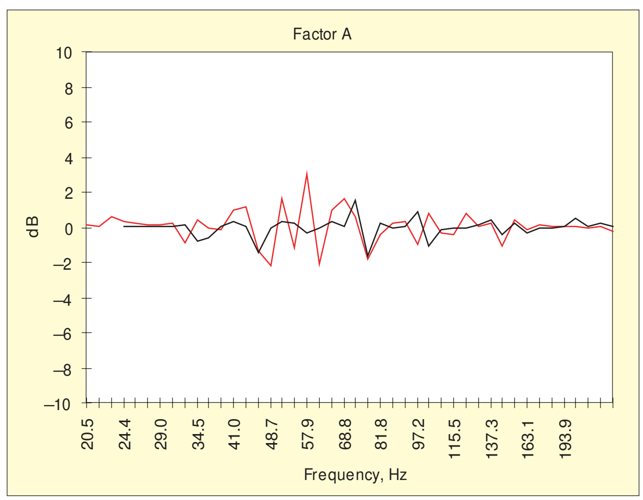

Figure 9. Effects plots for quad box to rail support.

The same DOE structure was exercised for the CAE model and the CAE effect plots were generated. The CAE effect plots can then be compared to the test effects as in Figure 5, which shows the measured effect in black and the CAE effect in red. Note the similarity between the two curves. The trend in the

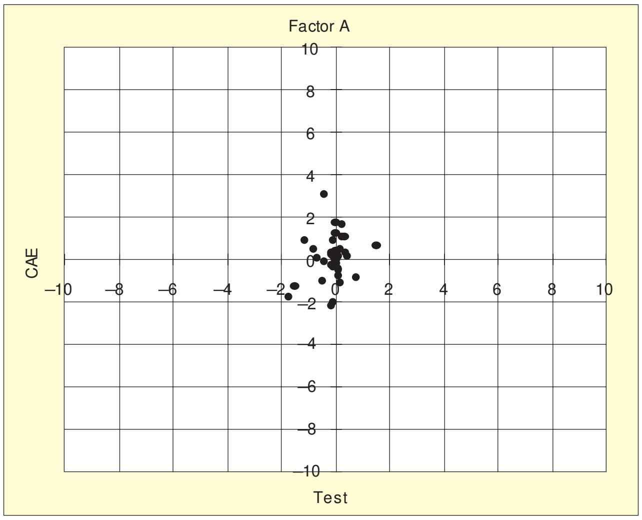

Figure 10. Cross plot for quad box to rail support.

Figure 11. Flagpole factor, trimmed body.

data suggests that the CAE is a good representation of the test. This information can be presented in another form by cross plotting the test effects versus the CAE effects, shown in Figure 6. Exact replication would be a straight line through the origin with unity slope. Detailed examination of the effect plot shows that although the plots are similar, some of the predicted effects are one to two frequency bins off, resulting in some scatter in the cross plot. These same plots are shown for the K brace at the front of the car in Figures 7 and 8.

Figures 7 and 8 show good physical representation of the factor effects in the finite element model. Optimization requires that the effects are small. Figures 9 and 10 show the transfer function for the quad box to rail support effect. Here it is important to note that around the cross plot origin there is a region of uncertainty due to the noise in the experiment and the effects could not be resolved.

Trimmed Body DOE Study

The FEA BIP model was trimmed to include closures (doors/fenders/hood/decklid), instrument panel, steering column/wheel assembly, seats, bumpers, fueltank, and other body items (mirrors, radio, antenna, fuel-filler door etc.) represented as a lumped mass. Carpeting (in door panels, dash panel, floor panel and package tray area) and mastic material on the floor and dash were simulated as "non structural masses," while paint, primer, nuts, bolts, washers, etc. were accounted through density adjustments.

The trimmed body was exercised for design effects using the same hardware changes and experimental design as exercised for the BIW experiment. The hardware changes are illustrated

Figure 12. Front K brace, trimmed body.

Figure 13. Inverted V factor, trimmed body.

in Figures 11-13.

The data were processed with the NVH CAE quality metrics to determine if the hardware changes resulted in statistically significant changes to the vehicle. The results are shown in Table 4. The test and CAE results for each run were compared to the test and CAE baseline runs respectively. The results as shown in Table 4 indicate that the CAE and the test show similar trends. However, unlike the Body-In-Prime (BIP) case, the design modifications do not seem to influence the trimmed body transfer functions significantly.

Directionally, the CAE predictions are as good as the tests. However, the CAE model overpredicts every DOE run compared to the tests. Figures 14-17 illustrate the effects plot for Factors D (inverted V brace) and E (front shock lateral brace).

1. The chosen design factors do not seem to significantly alter the trimmed body performance characteristics, unlike as in BIP. The metric d/s is no more than 0.7 for the body configuration with all 5 design factors, well within the statistical significance ($d/s < 1.0$) of concluding that all eight body configurations belong to the same ensemble.
2. CAE is directionally consistent with the tests but seems to overpredict the effect of the design factors.
3. The metric d/s for trimmed body baseline CAE is 1.82 with

Table 4. Metrics scores for run configurations, trimmed body.

	Test	CAE
Run 2	0.56	0.91
Run 3	0.00	0.00
Run 4	0.00	0.00
Run 5	0.30	0.85
Run 6	0.43	0.81
Run 7	0.00	0.00
Run 8	0.00	0.00
Run 9	0.70	1.00

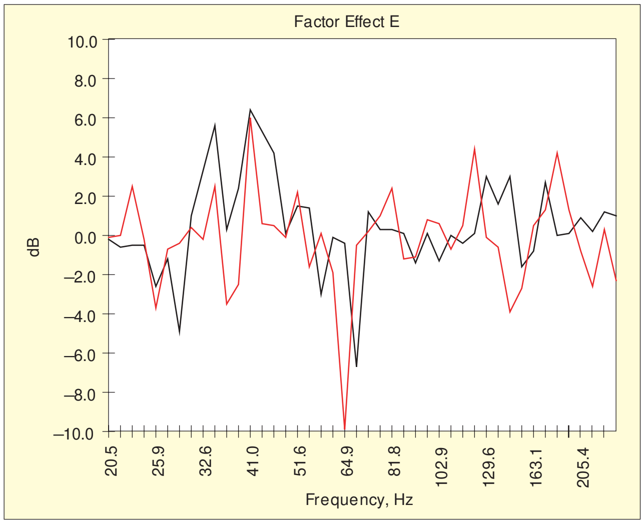

Figure 14. Effects plot for front K brace, trimmed body.

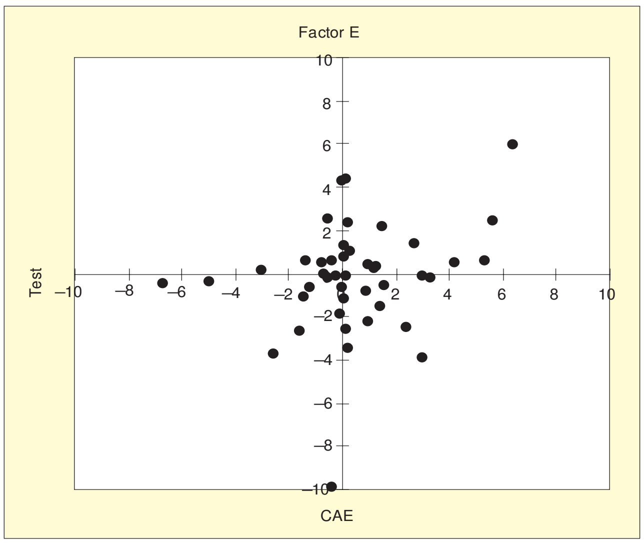

Figure 15. Cross plot for front K brace, trimmed body.

reference to the test baseline (ideally one would expect a 1.0). This was 1.62 at the BIP level.

4. For the chosen design factors and the responses, either the model is not good enough for design change evaluations, and/or the design changes are not significant enough to influence trimmed body characteristics beyond the noise level. This could very well explain scatter in the "scatter plot."

Conclusion

This article via two examples demonstrates that it is feasible to objectively assess the capability of a NVH CAE finite element model to span the design space. The models presented here were shown to be capable for Body-in-Prime predictions, while the predictability of the trimmed body was degraded.

It is possible to assess both baseline and model design capability. Any QOS for NVH CAE must include both components in its objective assessment of capability.

Acknowledgments

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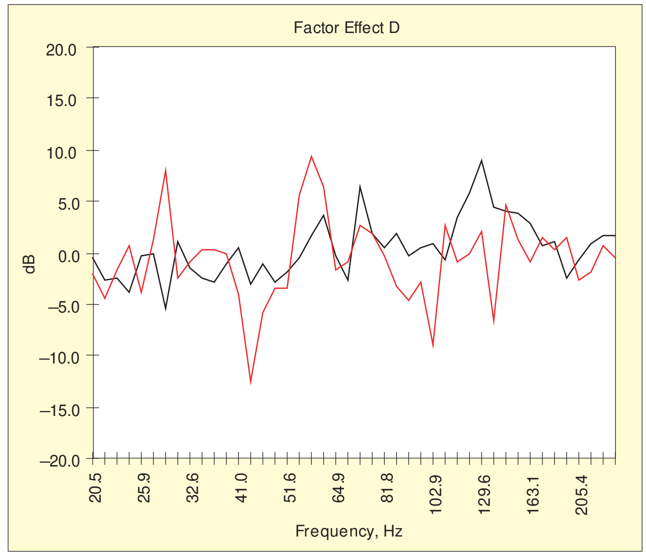

Figure 16. Effects plot for inverted V, trimmed body.

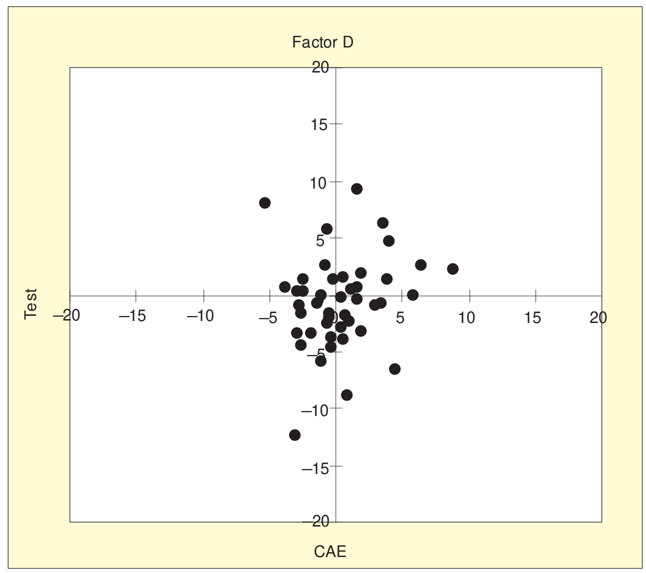

Figure 17. Cross plot for inverted V, trimmed body.

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