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Linear and Nonlinear Models of the Physiological Responses to Negative-to-Positive Gz Transitions

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Linear and Nonlinear Models of the Physiological Responses to Negative-to-Positive Gz Transitions

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1. SUMMARY

The identification and modeling of experimental data for negative-to-positive Gz (Push-Pull) transitions discussed in this paper is aimed at predicting typical and atypical physiological responses in order to develop Push-Pull countermeasures. A novel analysis of Push-Pull data in both the time and frequency domains was developed.

Eye-level blood pressure dynamics in response to Push-Pull transitions differ significantly from subject to subject. This individual sensitivity is much less profound in a sub-group of the tested subjects. Overall, the match between the predicted and measured eye-level blood pressure is much better with low Gz gradients than in the case of large Gz gradients. A model with a transfer function of low order (3 by 3) may be sufficient to match the behavior of eye-level blood pressure under both Push-Pull and positive Gz maneuvers. However, nonlinear models are required to fit blood pressure response data in a sub-group of subjects.

2. INTRODUCTION

The risk of G-induced loss of consciousness (GLOC) has become even more acute with the development of today's high performance aircraft that can withstand acceleration stress far in excess of a pilot's tolerance. Methods used to combat the fall in eye-level blood pressure include anti-G suit inflation, muscular straining manoeuvres, positive pressure breathing, or changes in the pilot's orientation with respect to the +Gz vector.

It is known that pilots' +Gz tolerance is reduced significantly when a +Gz exposure has been preceded by a -Gz exposure - the Push-Pull phenomenon [1]. This paper summarizes some early results of our research on the identification and analysis of dynamic models of the response of the cardiovascular systems of relaxed, unprotected subjects to Push-Pull transitions.

We applied a number of linear modeling techniques (e.g., recursive least squares, adaptive/recursive algorithms, and data segmentation based on AFMM (adaptive forgetting through multiple models)) to the experimental data [2]. These techniques enabled us to identify suitable model structures. Analysis of models for different subjects, as well as identification of discrepancies in responses of different subjects and the degree of correlation of their responses was undertaken. An attempt was also made to generalize individual models. A comparative analysis of a subject's physiological responses for positive-to-positive Gz transitions and negative-to-positive Gz transitions was performed. An attempt was also made to find out whether linear models are sufficient or nonlinear modeling is required.

3. MODELING OF PUSH-PULL EFFECTS

3.1 The Modeling and Prediction Algorithms

This section presents the results of the identification and analysis of a dynamic models representative of individual cardiovascular responses of relaxed, unprotected subjects exposed to Push-Pull manoeuvres, using data from the studies of Banks et al [1,3]. In the experiments reported in [1,3], Gz profiles were produced by moving a sliding bench back and forth along a track in a rotating horizontal plane. The blood pressure of the test subjects were measured using a Finapres device attached to a left-hand finger of the subject and secured over the right clavicle. Variable parameters of the Gz profiles were (i) time spent at -Gz and (ii) maximum +Gz exposure. Each experiment contained four types of runs:

- Zero Gz to +Gz (reference runs)
- Zero Gz to –Gz for t_1^- sec; then to +Gz and hold for t_1^+ sec; return to zero Gz.
- To -Gz for t_2^- sec; then to +Gz for t_2^+ sec; then to zero Gz.
- To -Gz for t_3^- sec; then to + Gz for t_3^+ sec; then to zero Gz.

In this preliminary study we examined data from the experiments performed on seven subjects. Input data used in the modeling investigation performed consisted of two files the measured Gz and the neck-level blood pressure. Neck-level blood pressure data were pre-processed in order to obtain the eye-level blood pressure.

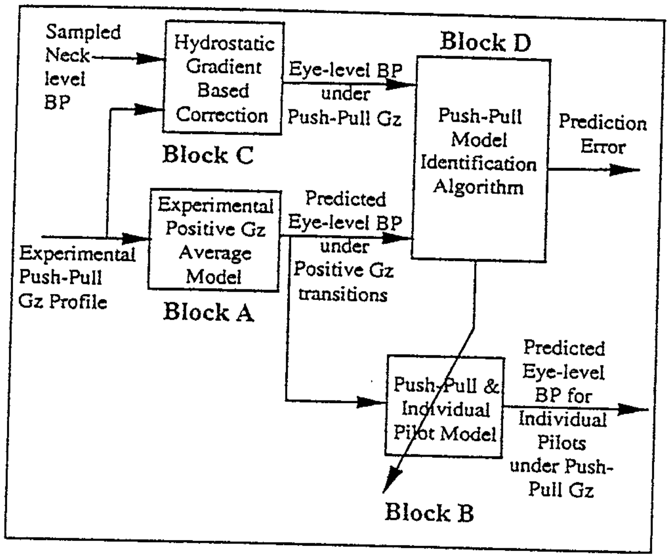

Figure 1: Push-Pull Modeling and Prediction Diagram

In these experiments, the subjects were fully restrained in a seated position on their backs, with their vertical axis (Gz axis) aligned with the direction of the seat movement along the track. Alternations in the subject's positive and negative Gz expsoure were achieved by repositioning the seat on the track and alternating the magnitude and direction of centripetal accelerations [1]. Positive Gz was obtained when the subject was positioned with feet facing outwards from the center of rotation, whereas the negative Gz corresponds to the subject positioned with his/her head facing outwards.

The modeling and prediction procedure developed in this paper for the case of Push-Pull responses is partially based on the transfer function (1) derived using the frequency domain response of the human body exposed to positive Gz transitions. The model (1) compares favourably to the model derived by Gillingham *et al.* [4]. The identification procedure developed in this report extends this Push-Push transfer function by adding a term that corresponds to the case of the Push-Pull Gz profiles. An important goal was to determine the possibility of using a unified model (expressed in terms of transfer functions) for both Push-Push and positive-to-positive Gz maneuvers. Another goal was to investigate and compare individual characteristics of subjects' responses and models under various Push-Pull maneuvers.

The scheme that has been implemented in order to model and predict a subject's eye-level blood pressure during Push-Pull manoeuvres is presented in Figure 1. The eye-level blood pressure is computed in **Block C** from the measured heart-level blood pressure corrected with the hydrostatic gradient from the heart to the eye. The Gz acceleration profile is an input into the simulation program that uses the empirical transfer function H(s) determined from positive-to-positive Gz transitions:

$$H(s)=\frac{BP(s)}{GZ(s)}=\frac{-3653.8s^6-1258.3s^5-9498.6s^4-1871.3s^3-4943.9s^2-508.6s-20.8}{112.8s^7+121.6s^6+354.6s^5+316.8s^4+250.1s^3+159.8s^2+27.9s+1} \quad (1)$$

The output of **Block A** is the predicted eye-level blood pressure. In general, this predicted blood pressure is not expected to fit the eye-level blood pressure in Push-Pull transitions since:

(i) the model in **Block A** has been computed from positive-to-positive Gz transitions while the Gz profiles used in this study are of the Push-Pull type;

(ii) the model in **Block A** does not take into account the individual physiological characteristics of each subject because it has been derived based on averaged data collected from a number of test subjects.

The purpose of the identification process in **Block D** is to calculate a corrective model to: (a) adapt the positive-to-positive Gz model to the Push-Pull blood pressure; and (b) account for the individual differences between subjects. The identification algorithm in **Block D** uses sampled (i.e., experimental) and predicted (based on the positive-to-positive Gz model) eye-level blood pressure values as its inputs. It produces two outputs:

(i) The Push-Pull correction model;

(ii) The standard deviation of the prediction errors.

Using the resulting Push-Pull correction model and the predicted eye-level blood pressure under Push-Push Gz (output of **Block A**), the predicted eye-level blood pressure for each individual subject under Push-Pull Gz is computed in **Block B** and compared with the experimental data. The predicted eye-level blood pressure for the individual subjects under the Push-Pull manoeuvres (output of **Block B**) is further used to evaluate eye-level blood pressure prediction accuracy for individual subjects under Push-Pull manoeuvres.

3.2 Push-Pull Modeling and Prediction Results

This section presents the results of modeling and prediction of a selected set of individual subject responses to different push-pull transitions. For each subject, data from one or two different push-pull experimental runs were analyzed. Two of the subjects were tested using the same Gz profile. Each figure below includes the following four plots:

1. the power spectra density of the neck-level blood pressure in dB of mmHg;
2. the eye-level blood pressure (solid line) predicted using the continuous transfer function defined by equation (1), together with the experimental eye-level blood pressure (dashed line);

3. the Gz profile;
4. the eye-level blood pressure (solid line) predicted using the new model identified for individual subjects that undergo Push-Pull transitions, together with the experimental eye-level blood pressure (dotted line).

Plots 2 and 4 of Figure 2 show the modeling results a subject during the Gz profile shown in plot 3. There is a poor match between the experimental and predicted blood pressure responses using the positive-to-positive Gz transfer function (1) during -Gz to +Gz transitions. However the match during +Gz to -Gz transitions is better.

The Push-Pull correction modeling did not significantly improved the match between the experimental and predicted blood pressure responses. The push-pull modeling algorithm (Block D, Figure 1) calculates coefficients of the transfer function polynomials, assuming initially that both the numerator and denominator are polynomials of degree 3. The resulting final optimal orders of the transfer function numerator and denominator polynomials, obtained by numerical trial and error, that yield the best fit are: 2 for the numerator and 2 for the denominator. The resulting transfer function is:

$$H(s) \;=\; 0.98\,\frac{1+0.58s+0.07s^2}{1+0.34s+0.18s^2} \qquad (2)$$

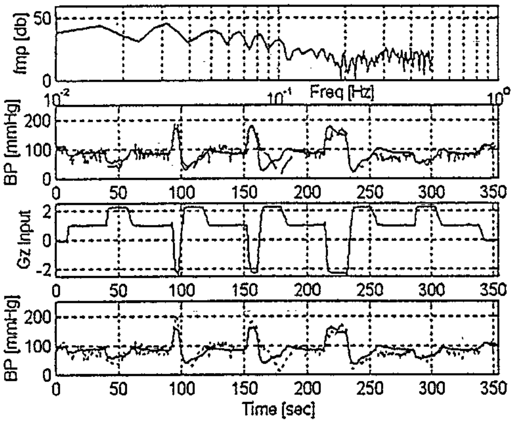

Figure 2: Modeling and Prediction Results for Session CA5

The gain of the transfer function (2) is close to 1 because the free term of the transfer function H(s) given by (1) has the correct steady state value. The frequency domain response presented in Plot 1 shows the presence of several relevant peaks at the following frequencies:

30 mHz, 50 mHz, 65 mHz, 80 mHz and 100 mHz.

The frequencies of the peaks are common (with very small variations) to all the test subjects during all push-pull exposures.

Figure 3 shows the prediction results for the same subject in a different Gz profile.

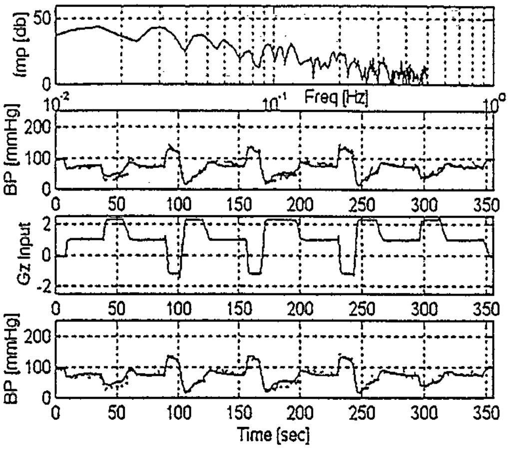

Figure 3: Modeling and Prediction Results for Session BC5

The modeling results show a good match between the experimental and predicted blood pressure responses during -Gz to +Gz transitions using the positive-to-positive Gz transfer function (1), as well as a very good fit during +Gz to -Gz transitions. The resulting optimal transfer function has 2 poles and 2 zeros, similar to the previous transfer function (2):

$$H(s) \;=\; 1.02\,\frac{1+0.63s+0.17s^2}{1+0.55s+0.31s^2} \qquad (3)$$

The degree of uncertainty in the identification of the transfer function polynomials is low with a standard deviation of 11.6 mmHg for the matching errors between the predicted eye-level blood pressure (based on the Push-Pull modeling) and the experimental eye-level blood pressure. This is only slightly lower than the variance of 12.6 mmHg in the matching errors between the experimental eye-level blood pressures and those predicted using the positive-to-positive Gz model (1) indicating that the positive-to-positive Gz model may also be used for the Push-Pull transitions of some subjects.

Plots 2 and 4 of Figure 3 show the modeling results another during the Gz profile shown in plot 3. There is a poor match between the experimental and predicted blood pressure responses during the -Gz to +Gz transitions using the positive-to-positive Gz transfer function (1), however,. the match during +Gz to -Gz portions is better. The Push-Pull correction did not significantly improve the match between the predicted and computed eye-level blood pressure

The transfer function for this case is given by:

$$H(s) \;=\; 0.96\,\frac{1+0.54s+0.07s^2}{1+0.49s+0.26s^2} \qquad (4)$$

Figure 4 shows the results of the simulation for same subject exposed to a different push-pull sequence.

The modeling and prediction results show a poor match between the experimental and predicted blood pressure responses during -Gz to +Gz transitions using the positive-to-positive Gz transfer function (1), whereas a better fit is obtained during +Gz to -Gz transitions. Compared with Plot 2, Plot 4 in Figure 4 shows that the Push-Pull correction modeling has improved the matching between the predicted and computed eye-level blood pressure. The transfer function for this case is given by:

$$H(s) \quad = \quad 0.9\,\frac{1+0.51s+0.06s^2}{1+0.56s+0.26s^2} \qquad (5)$$

The gain of the transfer function is smaller than (1), due to the poor matching between the eye-level blood pressure predicted based on equation (1) and the experimental eye-level blood pressure. The coefficients of the numerator and denominator polynomials in (5) are close to the values of the corresponding coefficients of (4).

The degree of uncertainty in the identification of the transfer function polynomials is of 13.6 mmHg for the matching errors between the predicted eye-level blood pressure (based on the Push-Pull modeling) and the experimental eye-level blood pressure. This is better than the variance of 18.1 mmHg in the matching errors between the experimental eye-level blood pressures and those predicted using the positive-to-positive Gz model (1) indicating that in this case the positive-to-positive Gz transition model (1) is not suitable for modeling the blood pressure responses to the Push-Pull transitions.

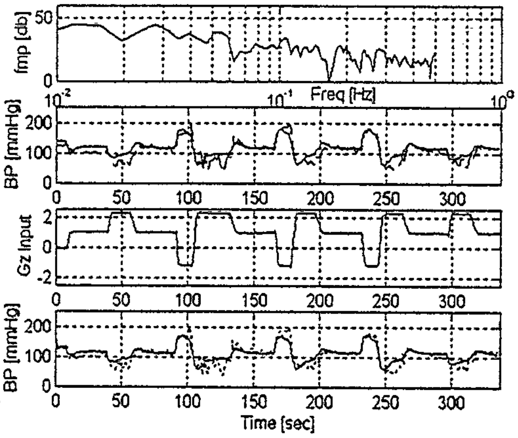

Figure 4: Modeling and Prediction Results for Session BB12

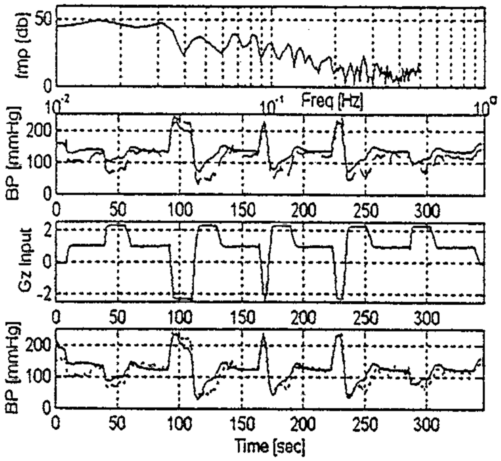

Figure 5: Modeling and Prediction Results for Session CC12

Plots 2 and 4 of Figure 5 show the modeling results for another subject during the Gz profile shown in plot 3. There is a poor match between the experimental and predicted blood pressure responses using the positive-to-positive Gz transfer function (1) during -Gz to +Gz transitions. The match during +Gz to -Gz transitions is better. The Push-Pull Correction has improved the match between the predicted and computed eye-level blood pressure. The transfer function for this case is similar to the previous subjects:

$$H(s) \quad = \quad 0.91\,\frac{1+1.25s+0.22s^2}{1+2.1s+0.85s^2} \qquad (6)$$

Based on the examples presented above, it is observed that in general:

1. either the prediction accuracy achieved with the transfer function (1) is good, or the Push-Pull correction improves the prediction accuracy significantly;
2. when the prediction accuracy of the transfer function (1) is poor, the DC (i.e., steady state) gain of the push-pull correction model is far from unity.

Specifically, the coefficients of the numerator and denominator polynomials in (6) differ significantly from the values of the corresponding coefficients in the other cases. The standard deviation of the matching errors between the eye-level blood pressure predicted based on the Push-Pull correction model and the eye-level blood pressure computed based on the measured neck-level blood pressure is 10.35 mmHg. This is better than the variance of 13.15 mmHg in the matching errors between the experimental eye-level blood pressures and those predicted using only the Push-Push model (1) and the eye-level blood pressure. In some cases the positive-to-positive Gz model (1) is not suitable for modeling the Push-Pull Gz transition and the Push-Pull Corrective Model has to be applied..

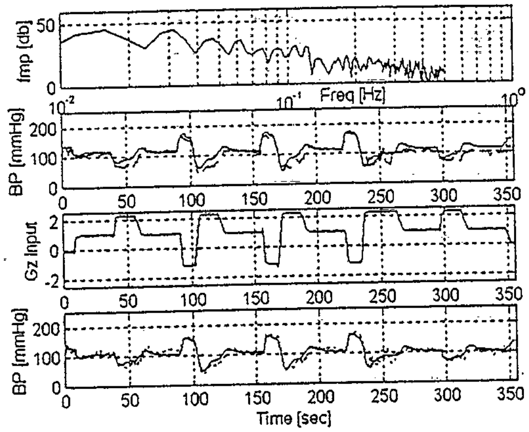

Figure 6: Modeling and Prediction Results for Session BE16

For other subjects, there was a poor match between the input the experimental and predicted eye-level using the trasnfer function (1) during *both* -Gz to +Gz and +Gz to -Gz transitions. In addition, the Push-Pull correction modeling did not improve the match. The physiological response of these subjects is nonlinear and a nonlinear modeling approach is required in these cases.

4. MODELING AND PREDICTION OF DIRECT PUSH-PULL MODEL

In order to further investigate the utilization of the positive-to-positive Gz averaged model given by Equation (1) for push-pull transitions, we have implemented a modeling and prediction scheme to compute a dynamic model of eye-level blood pressure as a function of the Push-Pull Gz signal based on direct experimental results. The purpose this section is to compare the following two models:

(i) **Model I:** The eye-level blood pressure model computed using the procedure described in section based on the combination of: (a) the positive-to-positive Gz averaged model computed from the frequency domain (1); and (b) the Push-Pull and individual subject corrective model as defined in Figure 1 discussed in Section 3;

(ii) **Model II:** The eye-level blood pressure model (called the *direct push-pull model* computed directly from: (a) the Push-Pull Gz profiles; and (b) the individual experimental eye-level blood pressures.

Figure 7 shows the prediction results for the experimental session CA17 with the Model II. The results in Figure 7 include the following plots:

1. the Gz profile;
2. the eye-level blood pressure (solid line) predicted using Model I, together with the experimentaleye-level blood pressure (dashed line);
3. the eye-level blood pressure (solid line) predicted using Model II, together with the eye-level blood pressure (dotted line) predicted using Model I;
4. the eye-level blood pressure (solid line) predicted using Model II and the experimental eye-level blood pressure (dotted line).

A signal pre-processing stage was needed in order to facilitate the computation of Model II. The pre-processing included a sign change and the *detrending* of the Gz and eye-level blood pressure signals.

The modeling and results show improved matching between the experimental eye-level blood pressure and the eye-level blood pressure predicted using Model II during both -Gz to +Gz and +Gz to -Gz transitions. The improvement is particularly noticeable in matching the blood pressure peak values. As compared with Plot 2, Plots 3 and 4 in Figure 7 show **the improved match of the blood pressure at both the maximum and minimum peaks.** However, it can be seen from Plot 4 that the Direct Push-Pull modeling not yield a perfect match between the dynamic time history of the predicted and the experimental eye-level blood pressure, since this subjects response is nonlinear. It can be also seen from Plot 3 that the dynamic time response of the eye-level blood pressure predicted using Model II is very similar to the eye-level blood pressure predicted using Model I and the standard deviation of the difference (3.15 mmHg) is caused mainly by the difference in the peak values of blood pressure.

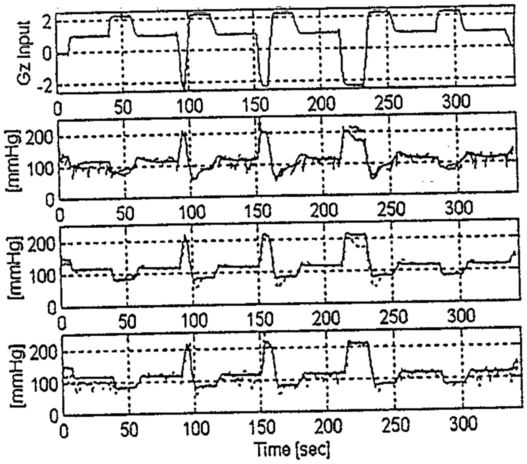

Figure 7: Modeling and Prediction Results for NCA17

The direct Push-Pull modeling algorithm calculates the coefficients of the transfer polynomials, assuming initially that both the numerator and denominator are polynomials of degree 4. The final optimal orders of the transfer numerator and denominator polynomials obtained by numerical trial and error are 3 for the numerator and 3 for the denominator. The resulting TF is:

$$H(s) = -21.4 \frac{(1+0.56s+0.18s^2) \quad (1+5.35s)}{(1+0.33s+0.21s^2) \quad (1+3.32s)} \qquad (7)$$

The transfer function defined by (7) consists of 3 terms:

(a) **First Term:** the gain of the steady state response, which is close to the theoretical value of -22 [4] and has the value identical to the steady state gain of the Rogers' model (eq. (6)-(10) in [5]);

(b) **Second Term:** a transfer function that is very similar to the function defined by (8) and represents the individual subject response;

(c) **Third Term:** a transfer function similar to the low-order transfer function of Rogers' model [5]:

$$H(s) = -21.4 \frac{(1+5.35s)}{(1+3.23s+5.17s^2)} \qquad (8)$$

One apparent difference between Rogers' model and the direct push-pull model is that the direct Push-Pull model matches the *drift* in the blood pressure response during constant Gz segments (e.g., a subject at rest after a Gz transition). The term "drift" refers to the slow drop in the blood pressure during constant Gz segments following a sharp Gz transition (Figure 8)[4].

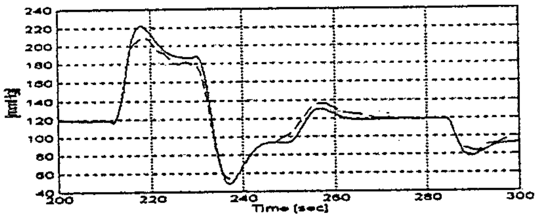

Figure 8: Detailed View of Eye-level BP Predicted by Rogers' and Push-Push Averaged Models *(Dashed line - Push-Push average model; Solid line- Rogers' Model)*

5. CONCLUSIONS

Blood pressure responses differ from subject to subject for relaxed Push-Pull and positive-to-positive Gz transitions. In the cases of subjects with extreme behavior, models of blood pressure responses seem to be more sensitive to the individual subject's responses than to the Gz transition type.

Overall, the match between the predicted eye-level blood pressure and the computed eye-level blood pressure is much better in the case of Gz profiles with low Gz gradients than in the case of Gz profiles with large Gz gradients. This is due to the nonlinear behavior and the lack of good matching for individual subjects with extreme behavior.

It appears from the modeling results that a model with a transfer function of low order (3 by 3) may be sufficient to match the behavior of eye-level blood pressure P under both Push-Pull and positive-to-positive Gz transitions. This model has been obtained by Direct Push-Pull Gz profile matching, and it is very close to the low-order Rogers' Model [5] with the exception that the Direct Push-Pull Model developed here captured the so-called drift behavior of the blood pressure. As a result, a low-order model may be used in the development of a model-based control scheme for the anti-G protection mask and suit valves.

All of the linear models investigated failed to match the eye-level blood pressure in cases of extreme behavior even when a model was computed using Direct Push-Pull modeling. And nonlinear modeling techniques must be used.

6. REFERENCES

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