PHASE LAG COMPENSATION IN REAL-TIME SUBSTRUCTURE TESTING BASED ON ONLINE SYSTEM IDENTIFICATION

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ABSTRACT :

In control of real-time substructure tests, time delay or phase lag of actuators is a very important issue. Research on phase lag of actuators shows that phase lag induces negative damping in such tests (Horiuchi *et al.* 1999). This can cause error and may lead to instability. Thus, phase lag of actuators should be reduced to improve accuracy and performance of real-time substructure tests.

Some compensation methods can be used to compensate phase lag in real-time substructure tests. The time delay compensations proposed by Horiuchi *et al.* (1996, 1999, 2001) use extrapolation techniques to predict displacements for the future. In these methods, there is no feedback mechanism to minimize the error of the prediction. The adaptive polynomial method (Wallace *et al.* 2005) and the compensation with feed-forward and feed-back control (Spencer *et al.* 2007) are more advanced since they have mechanisms to minimize error.

This paper introduces a new phase lag compensation, which is based on online system identification in the time domain. Since error of movement due to phase lag of actuator is very well related to the dynamic response of the system, this error can be estimated and then compensated. An advantage is that the compensator has a feedback mechanism to minimize the error of estimation and there is a possibility to develop the compensator to cope with time-varying or nonlinear systems. Numerical and experimental results on hydraulic systems with earthquake loads show the applicability of this compensation method for substructure tests in civil engineering.

KEYWORDS: time delay compensation, phase lag compensation, real-time substructure test, substructure algorithm, system identification

1. INTRODUCTION

The problem of phase lag / time lag or time delay of actuators in real-time substructure tests has been discussed in many publications (Horiuchi *et al.* 1996, 1999, 2001; Darby *et al.* 2001, Wallace *et al.* 2005; Spencer *et al.* 2007). Phase lag causes error and negative damping in the substructure solution which can lead to instability in the control of the test, if the negative damping is larger than the inherent damping in the structure (Horiuchi *et al.* 1996). In civil engineering applications, hydraulic systems for substructure tests usually have time lag of 8 ms to 40 ms (Horiuchi *et al.* 1999, Stoten *et al.* 2001, Spencer *et al.* 2007) or even larger (Wu *et al.* 2007). Phase lag compensation is a critical issue in real-time substructure tests in civil engineering. Once phase lag is well compensated, accuracy and stability of substructure test are improved.

Different phase lag compensations have been suggested for substructure tests. Based on predictive assumptions, the common principle of predictive methods is that the displacement is predicted one time lag ahead from the calculated displacement (and/or velocity and acceleration) at current time. Horiuchi *et al.* (1996, 1999, 2001) use a forward extrapolation technique. Their method assumes that time lag does not change much in a test and a deterministic number of steps can be chosen to be equivalent to time lag. But time lag varies with frequency (Spencer *et al.* 2007) and the assumption is not suitable for tests with a wide range of frequencies. Another method is based on adaptive polynomials (Wallace *et al.* 2005). It uses a least square fitting technique to predict the displacements one time lag ahead. This method has adaptive capability for compensation of both amplitude error and varying time lag. The adaptive polynomal method has experimental parameters (α,β,γ) which are obtained by using trial tests. The time lag compensation method with feed-forward and feed-back control based on a model of the testing system (Spencer *et al.* 2007) can be used effectively to compensate time lag of hydraulic actuators where the system is known or can be identified through an extra test.

The following phase lag compensation based on online system identification in the time domain has some advanced features such as adaptive capability for time-varying systems, both linear and nonlinear. The method is developed in the context of sub-step control in substructure tests.

2. PHASE LAG COMPENSATION BASED ON ON-LINE SYSTEM IDENTIFICATION

Instead of predicting displacements in the future, this method tries to establish an ideal control signal from historic data of computed displacements and the error between the target and response of the actuator.

The ideal control signal is the signal which leads to zero phase lag between response and target displacement. It is clear that, for a well controlled hydraulic system with phase lag, the ideal control signal exists. The phase (at each frequency) of the ideal control signal is ahead of the computed displacement. Because there is no information on the future, the ideal control signal cannot be obtained simply by shifting the phase on the computed displacement. Instead, it is estimated by a mechanism of identification and estimation. The ideal control signal $u_{ctl}(t)$ can be expressed as:

$$u_{ctrl}(t) = u_c(t) + \Delta u(t) \tag{1}$$

where $u_c(t)$ is the target displacement or the computed displacement and Δu(t) is called compensating displacement at time t. The key to compensation is to estimate the compensating displacement Δu(t) in order to minimize the error between response and target displacements.

In substructure tests with dynamic loads, the compensating displacement Δu is dynamically related to the computed displacement u_c. By using an appropriate data model to establish the dynamic relationship between the compensating displacement Δu (as output from the data model) and historical data of displacement and/or its time derivatives (as input to the data model), the estimator produces the compensating value Δu.

In Fig. 1, velocity $\dot{u}_c$ is used as the input to the data model. The compensating value Δu can be approximated as the difference between displacements at one time lag ahead and current time. If the time lag is short compared to the periods of the system, this difference depends strongly on the current velocity.

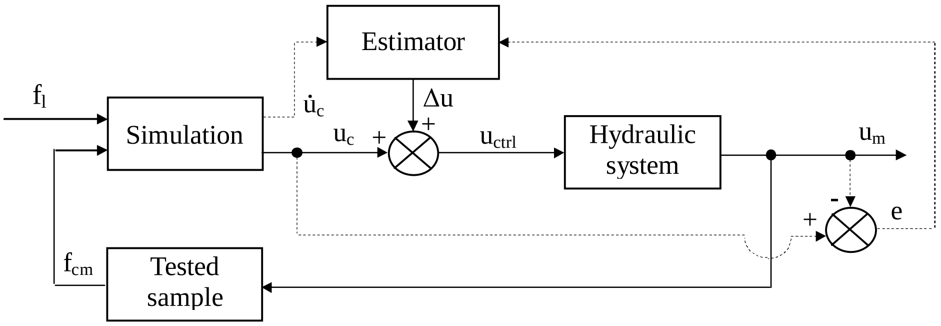


Figure 1: Substructure testing with time lag compensation based on system identification

Because the estimation is usually not perfect, there is an error between the response of the actuator and the target displacement (Eq. 2). The term e is called residual of time lag compensation which includes the error of the estimator and noise. The residual e must be accounted for in the estimator to minimize the control error.

$$e(t) = u_c(t) - u_m(t) \tag{2}$$

A compensation based on estimation must satisfy three critical requirements:

1. The model for estimation must represent the dynamic input-output relationship of a system well.

2. The estimator must handle error of estimation and noise to minimize the error of the output.
3. To estimate the parameters for this model, the system identification mechanism must work in "real-time".

For a mechanism to represent an input-output relationship, modeling concepts in the time- and frequency domain can be used. Time domain concepts are more suitable for dealing with historical data and on-line identification. Some recursive methods are available for data models working in the time domain and using on-line estimations. In real-time substructure tests, the historical data is updated at each sub-step or step. Therefore, parameters of models can be updated from their current states including information of historical data by using recursive identification.

Concerning the data model, a black-box model is used in the phase lag compensation because of its universal applicability. A linear black-box model is used for linear systems while a proper nonlinear one should be developed for a certain non-linear application.

Black-box models such as ARX (AutoRegressive with eXogenous inputs), ARMAX (AutoRegressive Moving Average with eXogenous input), OE (Output Error) or B-J model (Box - Jenkin) can be used. The ARMAX model is used in this research, because it is very accurate, can handle noise effectively and the computational cost is moderate.

A number of identification methods for parameter estimation and error minimization are available such as Prediction Error method (PE), Instrumental Variable methods (IV), Least Square Methods (LS), Maximum Likelihood method (ML) or Pseudo Linear Regression (PLR) (Söderström *et al.* 1989, L. Ljung 1999). A recursive method should be used in real time substructure tests. Important features of recursive identification methods are adaptive ability (with time-varying or nonlinear systems), small computational cost and easy tracking of time-varying parameters. In this work, the recursive PR method with forgetting factor is used.

There are two different time intervals for identification and estimation. The compensating value Δu should be estimated at each sub-step while the parameters for the data model should be updated at a lager time interval. Because the output of a system does not react to the input within the time lag, the parameters of the data model should not be identified within a time interval that is shorter than the time lag. The critical time interval Dt for parameter updating is given in Eq. (3).

$$Dt = k_{lag}.dt \geq \delta t \tag{3}$$

where k_{lag} is number of sub-steps for identification, dt is sub-step time interval and δt is maximum value of time lag in the considered range of frequencies.

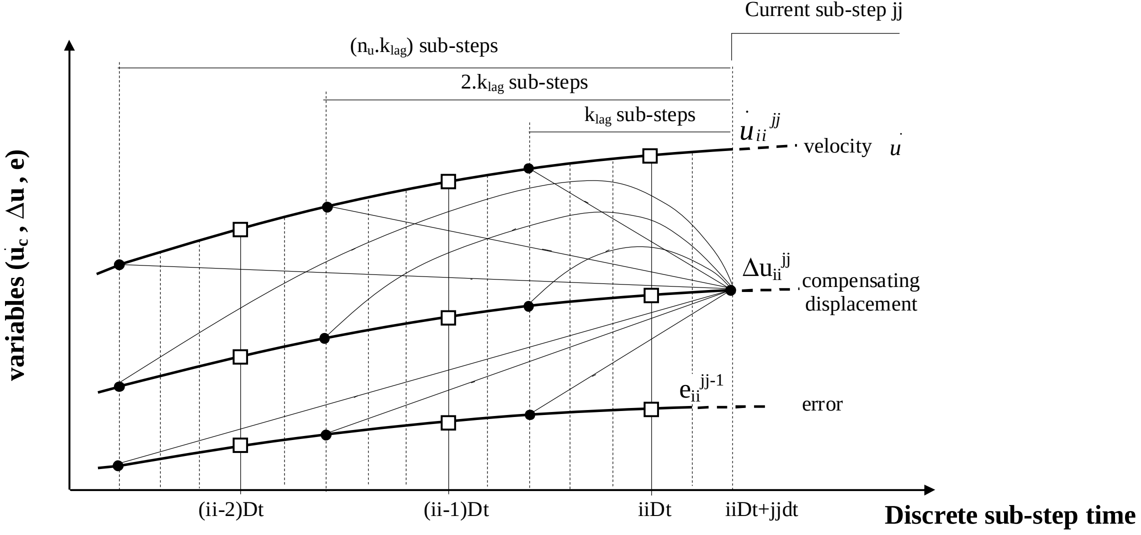


Figure 2: Scheme of identification and estimation of time lag compensation, illustration with number of sub steps for identification k_{lag}=5 and order n_u = 3

The scheme for estimating the model parameters and compensating displacements is shown in Fig. 2. The data for updating the parameters are shown as points with mark "□" while the data to estimate Δu are shown with mark "●". Using the current parameters, the value of Δu is calculated at each sub-step. At sub-step jj (jj ≤ k_{lag}), the data to estimate Δu_{jj} are the past values before (i.k_{lag}) sub-steps (with i = 1, 2, .. n_u and n_u is the order of the data model). At each sub-step jj, the parameters of the data model are calculated using a linear transition between the two last values of a parameter (Eq. 4).

$$\theta_{ii}^{jj} = (1 - \frac{jj}{k_{lag}})\theta_{ii-1} + \frac{jj}{k_{lag}}\theta_{ii} \quad ; \text{jj=1,..,k}_{\text{lag}} \tag{4}$$

With the methodology described above, the data model to estimate the compensating displacement is described in Eq. (5) ~ (7).

$$\Delta u_{ii}^{jj} = [\varphi_{ii}^{jj}]^T . \theta_{ii}^{jj} \tag{5}$$

$$\varphi_{ii}^{jj} = \left\{ -\Delta u_{ii-1}^{jj} \quad -\Delta u_{ii-2}^{jj} \quad \ldots -\Delta u_{ii-n_u}^{jj} \quad \dot{u}_{ii-1}{}^{jj} \quad \dot{u}_{i-2}{}^{jj} \quad \ldots \dot{u}_{ii-n_u}{}^{jj} \quad e_{ii-1}^{jj} \quad e_{ii-2}^{jj} \quad \ldots e_{ii-n_u}^{jj} \right\}^T \tag{6}$$

$$\theta = \left\{ a_1 \quad a_2 \quad \ldots \quad a_{n_u} \quad b_1 \quad b_2 \quad \ldots \quad b_{n_u} \quad c_1 \quad c_2 \quad \ldots \quad c_{n_u} \right\}^{\mathrm{T}} \tag{7}$$

where ii is the index for parameter updating, jj is the sub-step index after updating, φ is the vector of regression variables, θ is the vector of model parameters. The parameter θ is estimated by the recursive PLR method (L. Ljung, 1999) with forgetting factor λ ranging between 0.96 and 0.99.

Different sets of parameters {a_i , b_i} (i=1, … , n_u) lead to different relationships between amplitudes of the compensating displacement Δu and the computed velocity. Therefore, the parameter θ can also provide appropriate amplitudes for Δu to compensate the amplitude error in the transfer function of the hydraulic system.

3. IMPLEMENTATION AND EXPERIMENTATION

A suitable hardware concept is given in Fig. 3. The substructure control software with phase lag compensation is implemented in a real-time control system ADwin (Jäger Computegeteuerte Messtechnik 2006). Other hardware components are: U/I converter (voltage to current converter), servo valve, hydraulic cylinder, displacement transducer and amplifier 1. The servo valve is controlled directly through the software in ADwin.

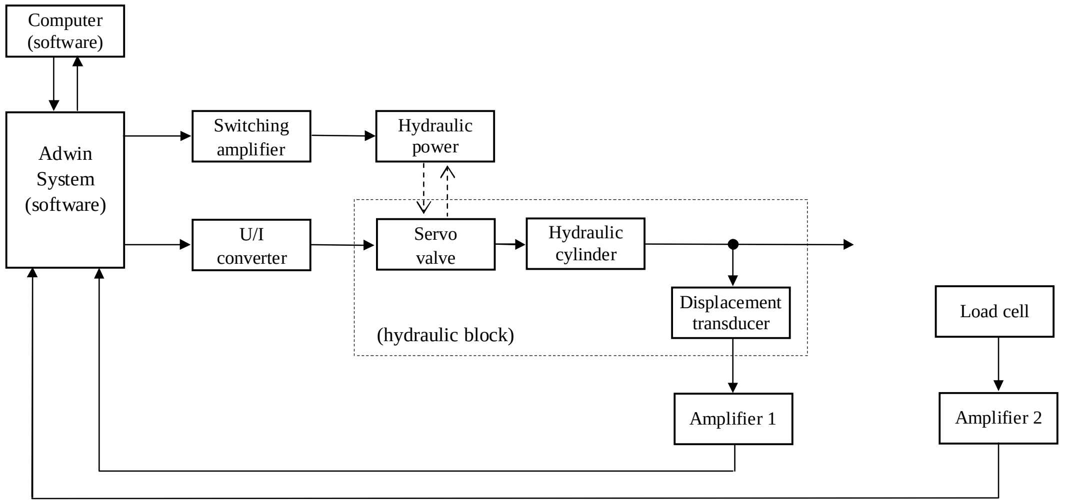
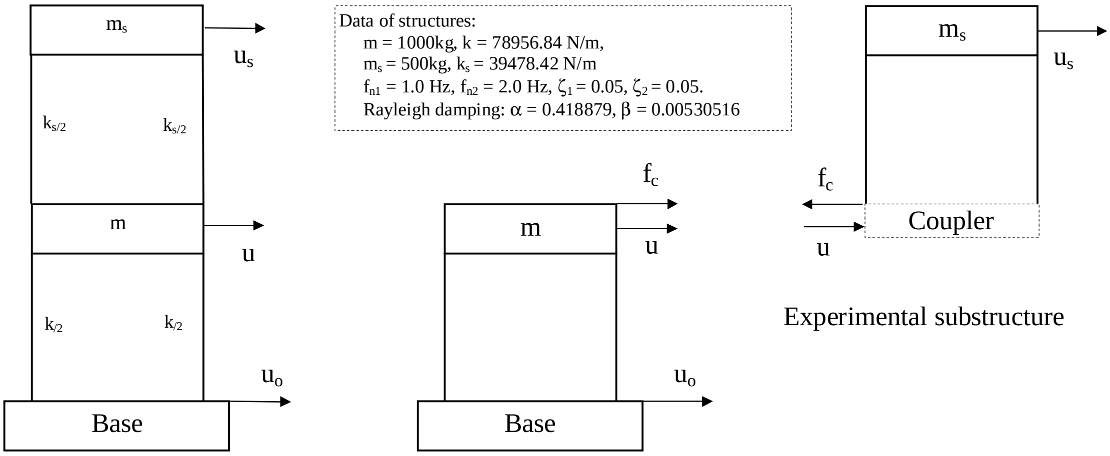


Figure 3: Hardware components of control and measurement systems for substructure tests

In displacement control, a combination of PID and MCS control (Stoten 1994, 2001) is used. PID control is used in the inner loop to stabilize the movement of the actuator while MCS control is used in the outer loop to improve the response in a wide range of frequencies. The time lag of the hydraulic system used in this research is about 12 ms to 16 ms.

To demonstrate the proposed phase lag compensation, a virtual substructure test was performed. In this test, the algorithm, control and measurement system, hydraulic system and numerical substructure are the same as in a real test. Only the experimental substructure is “virtual” meaning that it is numerically simulated using appropriate time integration methods such as the Duhamel integral which is exact for linear systems. The displacements and coupling forces between numerical and experimental substructure are compared to those of the complete structural model. This reference solution is obtained using Duhamel integral and mode superposition. The structural models are shown in Fig. 4.



Data of structures:
m = 1000kg, k = 78956.84 N/m,
m_s = 500kg, k_s = 39478.42 N/m
f_{n1} = 1.0 Hz, f_{n2} = 2.0 Hz, $\zeta_1 = 0.05$, $\zeta_2 = 0.05$.
Rayleigh damping: α = 0.418879, β = 0.00530516

Experimental substructure

Full model

Numerical substructure

Figure 4: The structural model used to demonstrate the proposed phase lag compensation

The response of the hydraulic actuator is shown in Fig. 5. A close fit with the target displacement can be observed. The result is excellent for both large and small displacements as well as different velocities.

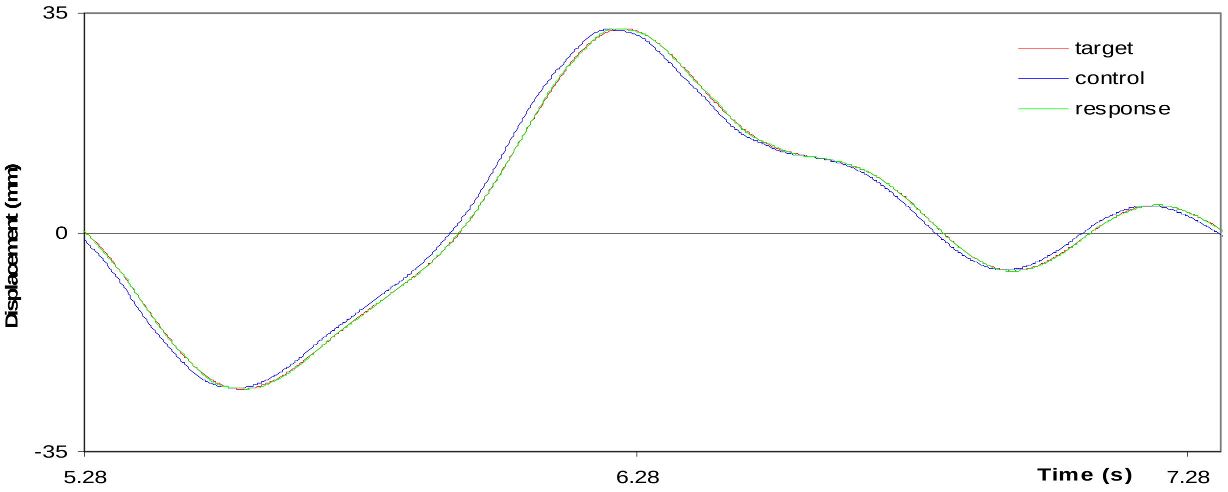


Figure 5: Response of the hydraulic cylinder with phase lag compensation

The cases with and without phase lag compensation are compared in Fig. 6. The hysteresis loop of the system with compensation (blue graph) has no visible area in contrast to the one without (red graph). It therefore reduces the negative damping due to phase lag almost to zero.

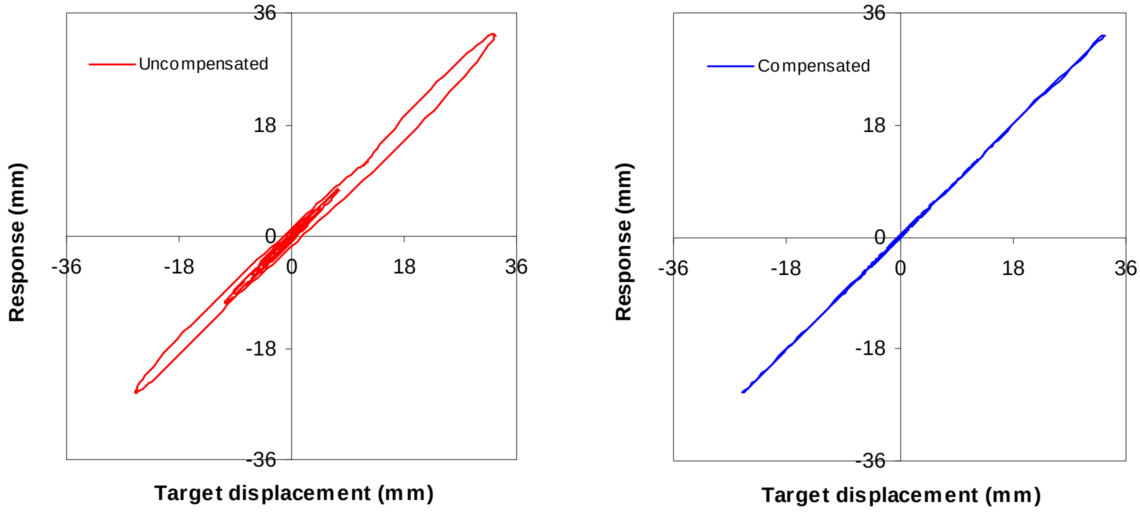


Figure 6: Comparison on phase plan between uncompensated and compensated systems. Compensation with n_u=6 and λ=0.98.

As a result, the difference between substructure solution and reference solution in case of phase lag compensation is significantly reduced (Fig. 7). This can be seen for displacements and coupling forces in both time and frequency domain.

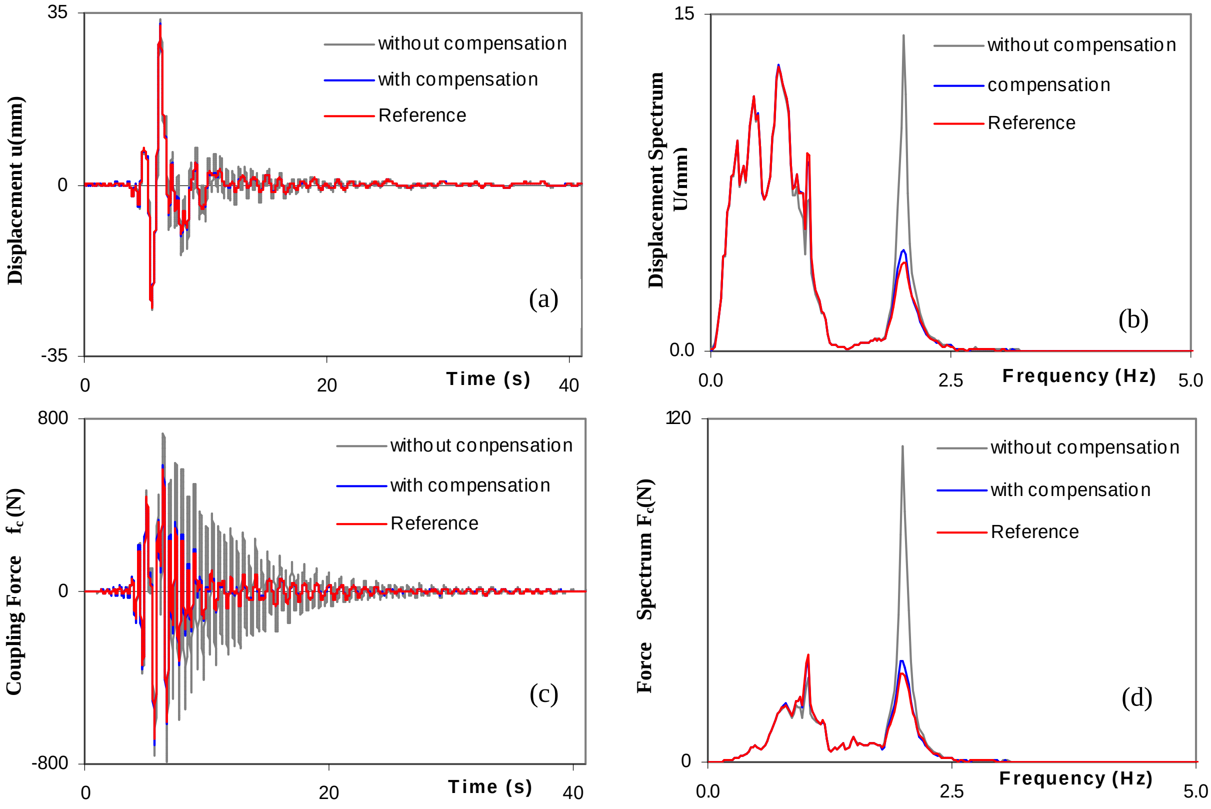


Figure 7: Comparison of substructure and reference solutions with and without phase lag compensation

4. SUMMARY AND CONCLUSIONS

A new method for compensating phase lag in real-time substructure tests with hydraulic systems is proposed. The method is based on online system identification using a black-box data model with recursive parameter identification.

The method was tested in a virtual substructure test consisting of the full test setup including hydraulics and measurement and control systems, but using a "virtual" specimen represented by a numerical model. The compensation effect is demonstrated on an example using a structural model under a realistic earthquake. The test results show that the method can well compensate phase lag of the hydraulic system and improve accuracy of substructure tests.

In this method, there is no need to separately estimate the parameters of the data model because the recursive mechanism will adjust them to the appropriate values. Their initial values can therefore be zero.

The compensation method can compensate not only phase lag but also amplitude errors of the hydraulic system. Noise uncorrelated to system displacements can be removed effectively.

The compensation has adaptive capacity for time-varying systems and non-linear phenomena that may occur during a test. The current working state of the hydraulic system enters into the parameters of the data model and the control signal is adjusted to adapt to any variations.

The accuracy of phase lag compensation depends on the accuracy of the data model and the convergence of the system identification method. To obtain high accuracy, the order of the data model must be chosen properly. Higher order can improve accuracy but increases the numerical effort. In any case, the order of data model must be smaller than the order of the testing system.

Since the updating time interval Dt cannot be smaller than the maximum time lag, phase lag compensation may not be suitable for rapid time-varying systems or substructure tests with high frequencies. To evaluate these limitations, further investigations on the dynamic behavior of this method are needed. Furthermore, stability limits also needed to be investigated.

REFERENCES

A.P. Darby, A. Blakeborough, and M.S. Williams (2001), *Improved control algorithm for real-time substructure testing*, Earthquake Engineering and Structural Dynamics, **30(3)**, pp431–448.

T. Horiuchi, M. Nakagawa, M. Sugano, and T. Konno (1996), *Development of a real-time hybrid experimental system with actuator delay compensation*, In Proc. 11th World Conf. Earthquake Engineering, Paper No. 660.

T. Horiuchi, M. Inoue, T. Konno, and Y. Namita (1999), *Real-time hybrid experimental system with actuator delay compensation and its application to a piping system with energy absorber*, Earthquake Engineering and Structural Dynamics, **28(10)**, pp1121-1141.

T. Horiuchi and T. Konno (2001), *A new method for compensating delay in time hybrid experiments*, Phil. Trans. R. Soc Lond., **A 359**, pp1893-1909.

Jäger Computegeteuerte Messtechnik (2006), *ADwin Pro – System and hardware description* , Germany.

L. Ljung (1999), *System Identification* - Theory for the users, Prentice Hall.

T. Söderström and P. Stoica (1989), *System Identification*, Prentice Hall.

D. P. Stoten, S. Bulut (1994), Application of the MCS algorithm to the control of an electrohydraulic system, IEEE-07802-1328-**3/94**, pp1742-1747.

D. P. Stoten and Eduardo G. Gomez (2001), *Adaptive control of shaking tables using the minimal control synthesis algorithm*, Phil. Trans. R. Soc. Lond. , **A 359**, pp1697-1723

B.F. Spencer Jr and Juan E. Carrion (2007), *Real-time hybrid testing of semi-actively controlled structure with MR damper*, Proceeding of 2nd Int. Conf. on Advances in Experimental Structure Engineering, China.

M. I. Wallace, D. J. Wagg and S. A. Neild (2005), *An adaptive polynomial based forward prediction algorithm for multi-actuator real-time dynamic substructuring*, Proc. R. Soc. A., **461**, pp3807–3826.

B. Wu, Q. Wang, P. B. Shing and J. Ou (2007), *Equivalent force control method for generalized real-time substructure testing with implicit integration*, Earthquake Engng Struct. Dyn., **26**.