Rocking Motion of a Bridge Foundation Platform

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Abstract

The goal of this research is to test the response of an oscillating foundation platform, which is positioned on soil and submerged by water. The oscillating platform is modeled as a linear spring-damper-mass oscillator with two perpendicular degrees of freedom. The platform is mounted so it can rotate around the directions corresponding to its main bending axis. A specially designed flume, which is 3000 mm long and 400 mm wide, allows for the investigation of different soil conditions and various flow depths. The oscillating platform is mounted elastically on a structure over the test section of the flume. Three synchronous linear drive motors apply the dynamic loads. Complex plane representation of the dynamic moments is used to identify the nonlinear fluid and soil moments. Additional goals are to detect the nonlinear fluid and soil coupling moments.

Introduction

This study will investigate how bridge foundations, such as spread footings, interact with soil and water during an earthquake. These interactions can occur at bridge foundations constructed under water (such as in a creek, a river or even a bay area) as well as at foundations constructed within the groundwater table. While an earthquake vibrates bridge foundations, the foundation might be exposed to a bi-directional rocking motion. When the rocking motion becomes significant, water can alternatively be sucked into gaps and pressed out of gaps that occur as the foundation rocks up and down. The effects of the interactions between the water and foundations can become significant and affect the bridge stability if the rocking motion is significant. Current design code for earthquake resistance does not consider these effects. This preliminary study will use a small-scale multi-hazard dynamic testing model to simulate these effects.

The experimental set-up is designed to study the fluid-soil structure interaction of a rigid foundation platform modeled as a two degree of freedom (2-DOF) oscillator using a forced oscillation experiment. The linear 2-DOF oscillator acts as a reference system to investigate the nonlinear behavior of the system when it interacts with fluid and soil. The identification concept to determine the fluid and soil moments and to analyze the coupling effects based on a forced oscillation test are similar used to model fluid dynamic damping and stiffness.
Kerenyi and Yen (2002) use forced oscillation tests to determine fluid and soil coefficients. The tests were conducted in a flume having a recess for different soil conditions. Billeter and Staubli (2000) investigated a multiple mode vibration test on a vertical plate. They use force coefficients and phase angle to compute fluid dynamic damping and mass. Staubli (1983) and Deniz (1997) used forced oscillation tests in a tow-tank to determine force coefficients and phase angle to describe the fluid dynamic system. Kerenyi and Staubli (2000) analyze the stability of a prism oscillating with two degrees of freedom in cross flow. Phase angle relationship is used to determine if the body is exited or damped.

Experimental Set-Up

The experimental set-up consists of two major subsystems: a flume to simulate various flow and riverbed conditions and the shaking device to apply different dynamic loadings.

Flume

The flume consists of a 1300 mm long inlet and a 2000 mm straight channel (Figure 1). The upstream flow conditioning is achieved using filter mats, a honeycomb flow straightener, and a carefully designed trumpet-shaped inlet. The flume is designed to have a uniform flow distribution over the width and to have fully developed turbulent flow (following Prandtl's velocity distribution) at the test section. The recess at the test section is 400 mm x 300 mm (length x width) and 80 mm deep, and can be filled with sand particles of various sizes. The roughness of the fixed bed upstream of the recess can be varied according to the sand particles used in the recess. A 25 l/s pump provides the flume with water, which is stored under the flume in a water tank. A flow meter measures the discharge and an ultra sonic flow depth meter determines the flow depth. A laser distance meter, which is mounted on a portal robot, can scan scour holes during test runs. The flow velocity is measured with an electro magnetic velocity probe.

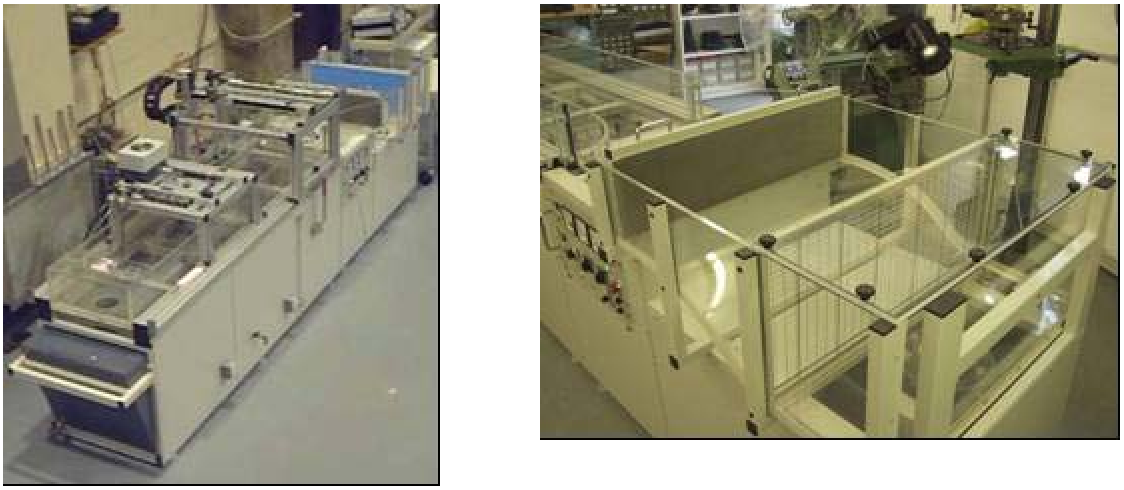

Figure 1. Test flume and trumpet shaped inlet

Shaking Device

The shaking device is mounted above the flume on a rigid frame at the test section. Three synchronous linear drive motors apply dynamic forces up to 10 Hz. Three lasers provide the feedback signal for the linear drive motors. The driving signals have to be superposed to achieve the rocking movement (Figure 2).

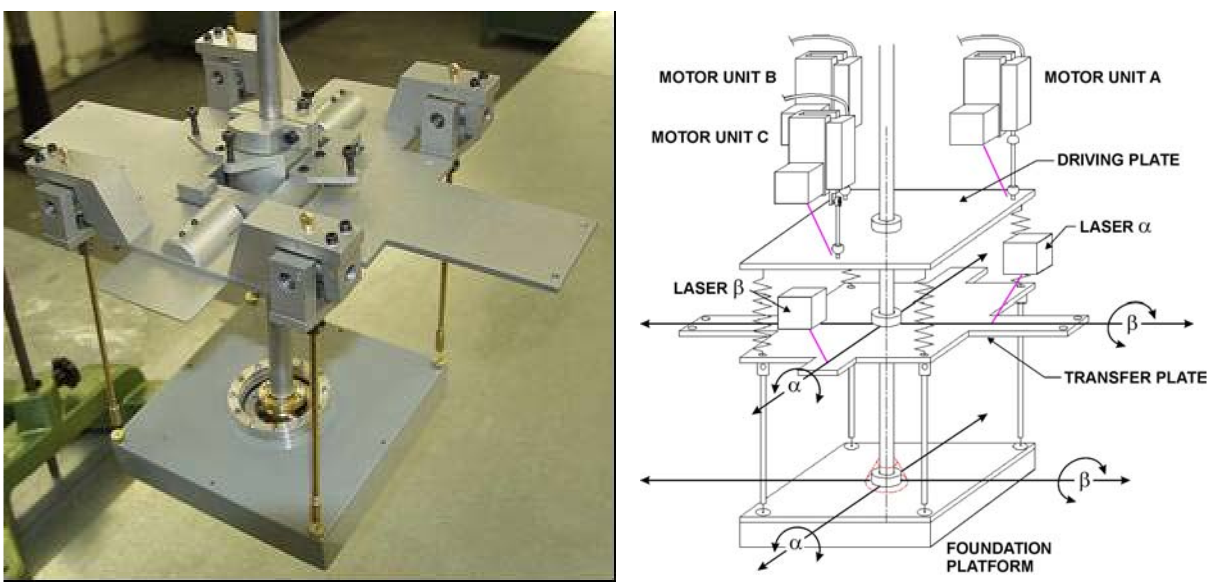

Figure 2: Shaking device

Band limited random noise can be used to simulate earthquake loading. The platform is mounted so it can rotate around the directions corresponding to its main bending axis. The foundation platform is linked to a transfer plate using four thin columns. The transfer plate is elastically mounted to the diver system. Using different coil springs for the elastical support can vary the natural frequency. The mechanical (structural) subsystem represents a linear spring-damper-mass oscillator with two perpendicular degrees of freedom, which is lightly damped to study a significant peak resonant response. The damping ratio is determined by the Half-Power (Band-Width) method. The angular response displacement is measured with a laser distance meter and the angular response acceleration with accelerometers. The angular response velocity is determined by integrating the angular response acceleration. Four load cells measure the applied dynamic loading.

Mathematical Background

The objective of this research, how the equilibrium of forces change by adding fluid and soil to the oscillating foundation platform to determine the non-linear behavior of the additional stiffness and damping coefficients (Figure 3).

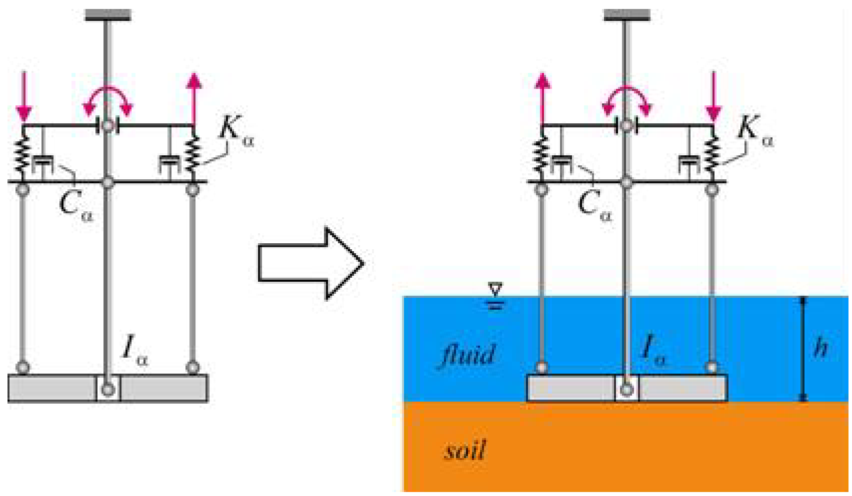

Figure 3: Fluid-soil spring-damper system

Identification Procedure

The identification procedure is based on the idea of a forced oscillation experiments used to determine fluid and soil dynamic stiffness and damping. Additional damping and stiffness coefficients can model the fluid dynamic and the soil subsystem (equation 1), which are functions of several parameters (e.g., amplitude and frequency). The mechanical subsystem has no coupling coefficients, because the degrees of freedom are orthogonal.

$$\mathbf{I}\begin{pmatrix}\ddot{\alpha}(t)\\ \ddot{\beta}(t)\end{pmatrix}+\mathbf{C}\begin{pmatrix}\dot{\alpha}(t)\\ \dot{\beta}(t)\end{pmatrix}+\mathbf{K}\begin{pmatrix}\alpha(t)\\ \beta(t)\end{pmatrix}+\begin{pmatrix}\overline{C}_\alpha & \overline{C}_{\alpha,\beta}\\ \overline{C}_{\beta,\alpha} & \overline{C}_\beta\end{pmatrix}\begin{pmatrix}\dot{\alpha}(t)\\ \dot{\beta}(t)\end{pmatrix}+\begin{pmatrix}\overline{K}_\alpha & \overline{K}_{\alpha,\beta}\\ \overline{K}_{\beta,\alpha} & \overline{K}_\beta\end{pmatrix}\begin{pmatrix}\alpha(t)\\ \beta(t)\end{pmatrix}=\begin{pmatrix}M_{\alpha,o}\exp(i\,\overline{\omega}_\alpha t)\\ M_{\beta,o}\exp(i\,\overline{\omega}_\beta t)\end{pmatrix} \quad (1)$$

where

$$\mathbf{I}=\begin{pmatrix}I_\alpha & 0\\ 0 & I_\beta\end{pmatrix},\ \mathbf{C}=\begin{pmatrix}C_\alpha & 0\\ 0 & C_\beta\end{pmatrix},\ \mathbf{K}=\begin{pmatrix}K_\alpha & 0\\ 0 & K_\beta\end{pmatrix}. \quad (2)$$

For the tests described here only the exciting frequencies ω_α, ω_β and the amplitudes α_o, β_o will be varied, by keeping the soil conditions and the flow depth h constant.
The identification concept is based on the balance of moments acting on the linear mass two degree of freedom (2-DOF) oscillator (Figure 4) under steady state harmonic condition whereby the total response for both coordinates is:

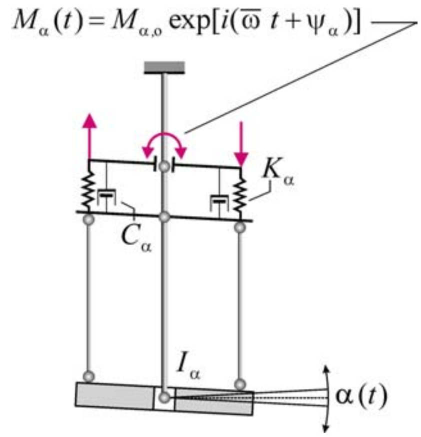

Figure 4: Linear 2-DOF system showing the α-coordinate

$$\alpha(t) = \alpha_o \exp(i\varpi t) \text{ and } \beta(t) = \beta_o \exp[i(\varpi t + \varphi)] \quad (3)$$

Moment equilibrium requires that the sum of the inertial $M_{I,i}(t)$, damping $M_{D,i}(t)$ and stiffness moments $M_{S,i}(t)$ for $i = \alpha, \beta$ are equal the applied load

$$\begin{aligned} M_\alpha(t) &= M_{\alpha,o} \exp[i(\varpi\, t + \psi_\alpha)] \\ M_\beta(t) &= M_{\beta,o} \exp[i(\varpi\, t + \psi_\beta)] \end{aligned} \quad (4)$$

Using equation (3), these moments are:

$$\begin{aligned} M_{I,\alpha} &= I_\alpha \ddot{\alpha}(t) = -I_\alpha \varpi^2 \alpha_o \exp(i\varpi t) \\ M_{I,\beta} &= I_\beta \ddot{\beta}(t) = -I_\beta \varpi^2 \beta_o \exp[i(\varpi t + \varphi)] \end{aligned} \quad (5)$$

$$\begin{aligned} M_{D,\alpha} &= C_\alpha \dot{\alpha}(t) = i K_\alpha \varpi \alpha_o \exp(i\varpi t) \\ M_{D,\beta} &= C_\beta \dot{\beta}(t) = i C_\beta \varpi \beta_o \exp[i(\varpi t + \varphi)] \end{aligned} \quad (6)$$

$$\begin{aligned} M_{S,\alpha} &= K_\alpha \alpha(t) = K_\alpha \alpha_o \exp(i\varpi t) \\ M_{S,\beta} &= K_\beta \beta(t) = K_\beta \beta_o \exp[i(\varpi t + \varphi)] \end{aligned} \quad (7)$$

along with the applied loading, are shown as vectors in the complex plane (Figure 5) also shown is the closed polygon of moments required for equilibrium in accordance with equation (8)

$$M_{I,i}(t) + M_{D,i}(t) + M_{S,i}(t) = M_i(t) \quad \text{for } i = \alpha, \beta \tag{8}$$

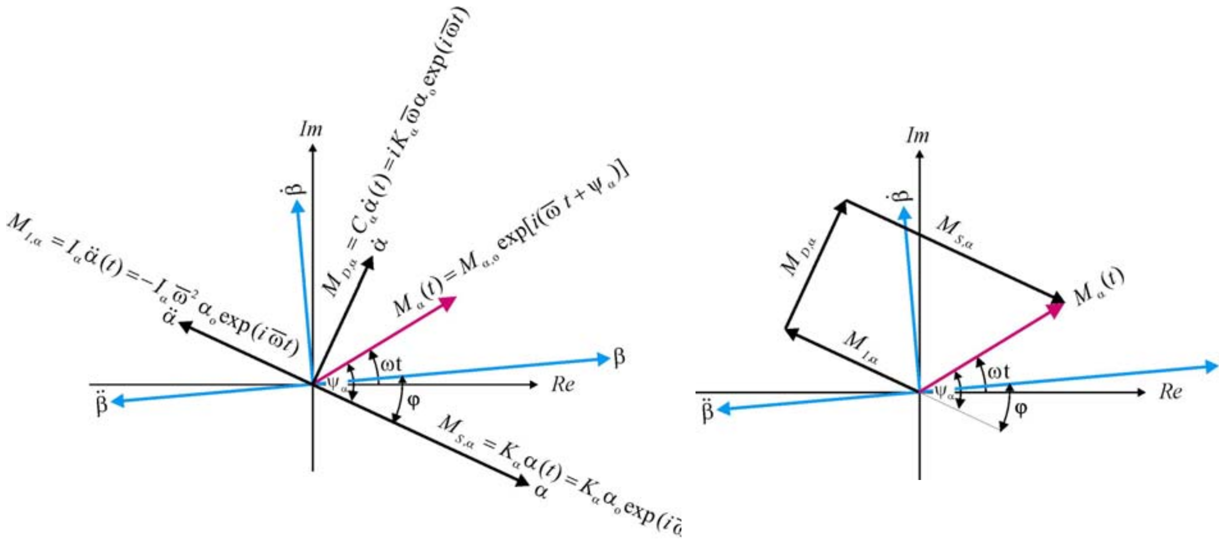

Figure 5: Steady state harmonic moments using viscous damping in a complex plane representation and closed moment polygon representation (moments are plotted only for the α-coordinate

Inertial, damping, and spring moments as given in equation (5-7) are in phase with the angular acceleration, velocity, and displacement motions, respectively.

If the 2-DOF linear mass oscillator interacts with flow and soil additional damping and stiffness moments are required for equilibrium. These additional moments also include fluid and soil-coupling moments as the 2-DOF system interacts with fluid and soil (Figure 6 and 7). These moments are frequency and amplitude dependent. To identify

$$\overline{C}_\alpha, \overline{C}_\beta, \overline{K}_\alpha, \overline{K}_\beta \tag{9}$$

one degree of freedom has to be blocked, as indicated in figure 6, where the β-coordinate is blocked. In this case the additional fluid and soil moments by substituting equation (3) are

$$\overline{M}_{S,\alpha}(t) = \overline{K}_\alpha(\alpha_o, \overline{\omega})\,\alpha(t) = \overline{K}_\alpha(\alpha_o, \overline{\omega})\,\alpha_o \tag{10}$$

$$\overline{M}_{D,\alpha}(t) = \overline{C}_\alpha(\alpha_o, \overline{\omega})\,\dot{\alpha}(t) = i\,\overline{C}_\alpha(\alpha_o, \overline{\omega})\,\overline{\omega}\,\alpha_o \tag{11}$$

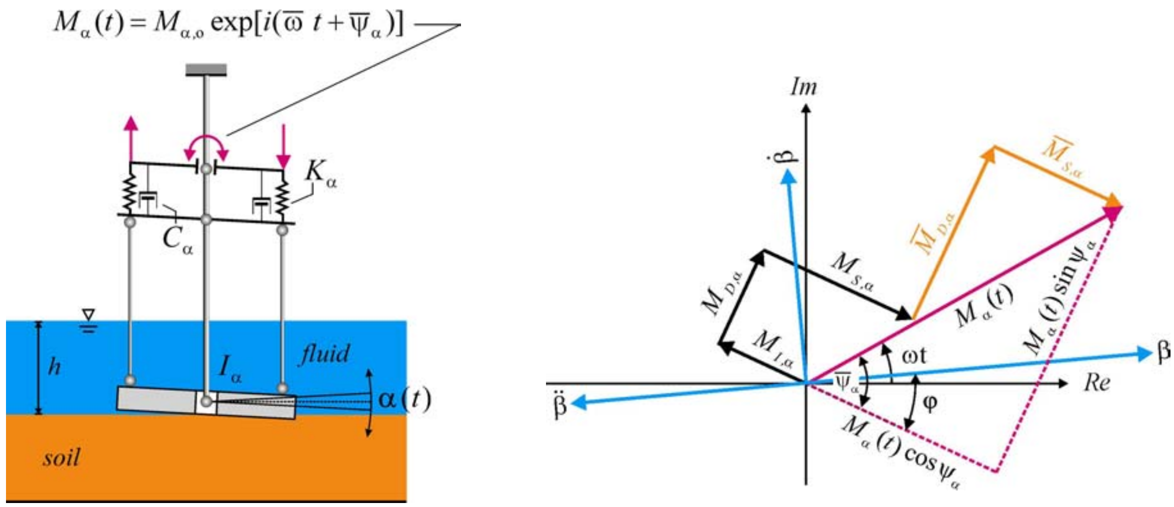

Figure 6.: 2-DOF system interacting with fluid and soil and closed polygon representation including additional damping and stiffness moments for the α-coordinate

To determine these additional moments cross power spectrum is used to compute the phase angle ψ_α between body response angular displacement amplitude α_o and applied dynamic moment amplitude $M_{\alpha,o}$. The moments can be expressed by equilibrating the dynamic moment components

$$\overline{M}_{S,\alpha} = M_\alpha(t)\cos\overline{\psi}_\alpha - M_{S,\alpha} - M_{I,\alpha} \tag{12}$$

$$\overline{M}_{D,\alpha} = M_\alpha(t)\sin\overline{\psi}_\alpha - M_{D,\alpha} \tag{13}$$

Substituting equations (5) to (7) and equations (10) and (11) into equation (12) and (13), one obtains the fluid-soil coefficient functions for the α-coordinate

$$\overline{K}_\alpha(\alpha_o,\varpi) = \frac{M_{\alpha,o}(t)\cos\overline{\psi}_\alpha - K_\alpha\alpha_o - I_\alpha\varpi^2\alpha_o}{\alpha_o} \tag{14}$$

$$\overline{C}_\alpha(\alpha_o,\varpi) = \frac{M_{\alpha,o}(t)\sin\overline{\psi}_\alpha - C_\alpha\varpi\,\alpha_o}{\varpi\,\alpha_o} \tag{15}$$

To identify the coupling coefficients

$$\overline{C}_{\alpha.\beta}, \overline{C}_{\beta,\alpha}, \overline{K}_{\alpha,\beta}, \overline{K}_{\beta,\alpha} \tag{16}$$

the 2-DOF oscillator is exited in both directions. As indicated in figure 7 for the α-coordinate additional fluid-soil coupling damping and stiffness moments are required for equilibrium.

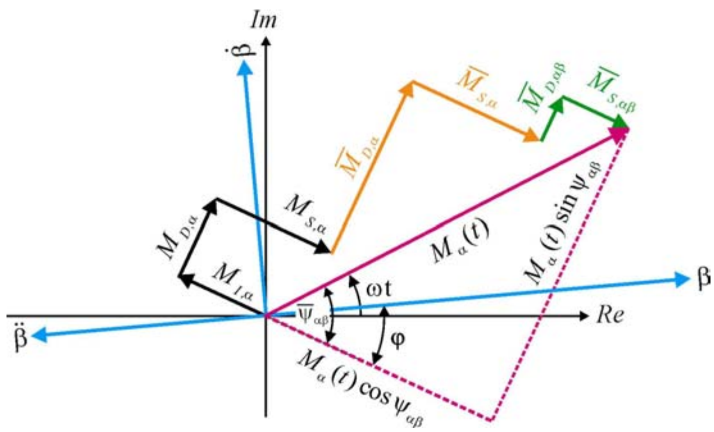

Figure 7.: Complex plane representation of the 2-DOF system interacting with fluid and soil to determine the additional coupling moments for the α-coordinate

Again cross power spectrum is used to compute the phase angle $\psi_{\alpha\beta}$ between body response angular displacement amplitude α_o and applied dynamic moment amplitude $M_{\alpha,o}$ and to determine the phase angle between response angular displacement amplitude α_o and β_o. The moments can be expressed by equilibrating the dynamic moment components (for the α-coordinate)

$$\overline{M}_{S,\alpha\beta} = M_{\alpha}(t)\cos\overline{\psi}_{\alpha\beta} - M_{S,\alpha} - M_{I,\alpha} - \overline{M}_{S,\alpha}\,, \tag{17}$$

$$\overline{M}_{D,\alpha} = M_{\alpha}(t)\sin\overline{\psi}_{\alpha\beta} - M_{D,\alpha} - \overline{M}_{D,\alpha}\,. \tag{18}$$

using the fluid and soil moments derived in equation (12 and 13). Coordinate transformation leads to

$$\overline{K}_{\alpha,\beta}\,\beta(t) = \overline{M}_{D,\alpha\beta}\sin\varphi + \overline{M}_{S,\alpha\beta}\cos\varphi\,, \tag{19}$$

$$\overline{C}_{\alpha,\beta}\,\dot{\beta}(t) = \overline{M}_{D,\alpha\beta}\cos\varphi - \overline{M}_{S,\alpha\beta}\sin\varphi\,. \tag{20}$$

Substituting equation (3) into equation (19) and (20) one obtains the coupling coefficients for the (α-coordinate):

$$\overline{K}_{\alpha,\beta}(\beta_o,\overline{\omega}) = \frac{\overline{M}_{D,\alpha\beta}\sin\varphi + \overline{M}_{S,\alpha\beta}\cos\varphi}{\beta_o} \tag{21}$$

$$\overline{C}_{\alpha,\beta}(\beta_o,\overline{\omega}) = \frac{\overline{M}_{D,\alpha\beta}\cos\varphi - \overline{M}_{S,\alpha\beta}\sin\varphi}{\overline{\omega}\,\beta_o}\,. \tag{22}$$

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