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# Investigation of a slip joint connection between the monopile and tower of an offshore wind turbine

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## Introduction

To circumvent current industry problems related to the settling of grouted connections, a steel-to-steel or *slip joint* connection is proposed for fitting a transition piece onto an installed monopile foundation. A slip joint consists of two conical sections, one attached to the top of the foundation pile and the other to the bottom of the transition piece. The dimensions of the two sections are chosen so as to have one fit closely inside the other in the same way as two inverted cups – see figure 1. Figure 2 shows an onshore wind turbine which was designed and installed with a slip joint connection and has already been in operation since 1995.

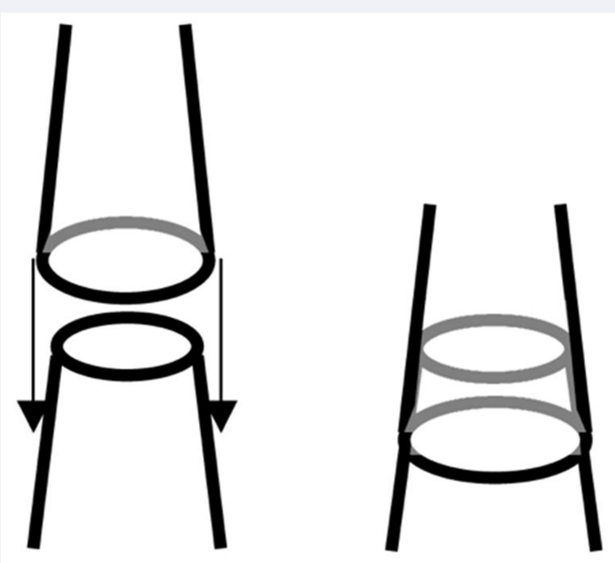


Figure 1: Slip joint concept.

Figure 2: Slip joint connection on a wind turbine at Scheveningen in the Netherlands [1].

## Objectives of this study

The joint has not yet been applied offshore. Therefore two different aspects of the development of such a joint for offshore applications are considered, namely:

1. a simplified dynamic analysis of its installation under own weight with and without initial velocity,
2. a determination of its static capacities (axial and bending) in the in-place situation by means of a FE model.

## 1 Dynamic analysis

The two conical cylinders are represented as rigid beams as shown in figure 3. The geometrical stiffness of the top cone in the radial direction is represented by linear springs, whilst the bottom cone is assumed fixed.

The contact stiffness between the bodies in normal and tangential direction are represented by two linear springs. In figure 4 the 1-D model of the slip joint with rigid beams and contact stiffnesses is shown.

The upper cone can respond to the gravitational load by either sticking or slipping, similar to the slip-stick systems presented by Popp [2], Den Hartog [3] and Hong et al [4.] Equations of motion (EOM) can be derived for stick and slip. The EOM for the stick condition are given below. The EOM of slip are equal to those of stick, except that the tangential spring force is replaced by the friction force $F_r$.

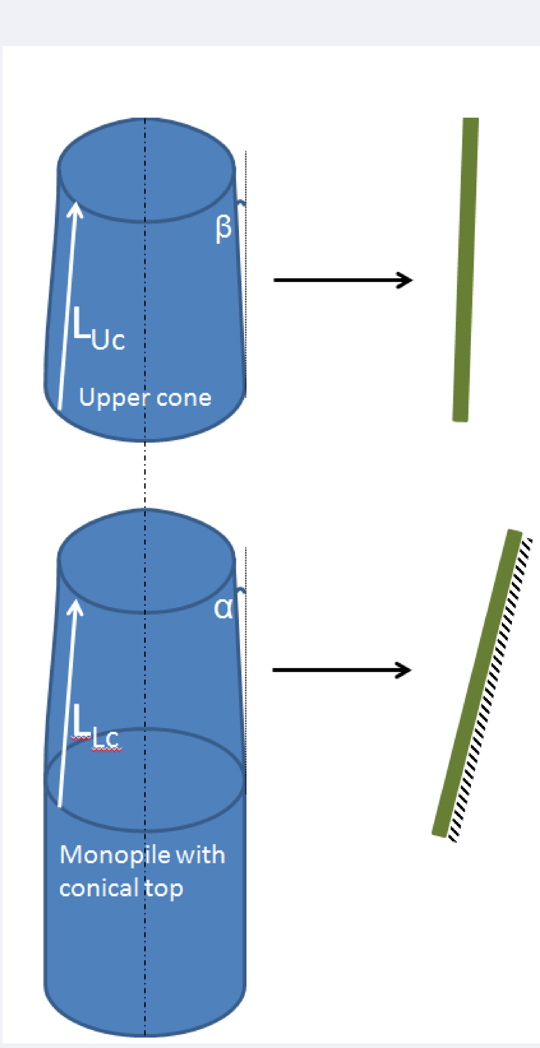



Figure 3: Representation of the slip joint 1-D model

### Equations of motion

$$M\ddot{u} = -\int_0^L K_{rr} u dX - \int_0^L K_{rr}(\frac{L}{2} - X) sin(\theta) dX - K_N u_N cos(\alpha) - K_\tau(u_\tau - x_\tau) sin(\alpha)$$

$$M\ddot{v} = K_N u_N sin(\alpha) - K_\tau(u_\tau - x_\tau) cos(\alpha) - F_z$$

$$J\ddot{\theta} = -\int_0^L K_{rr} u\,(\frac{L}{2} - X) dX - \int_0^L K_{rr}(\frac{L}{2} - X)^2 sin(\theta) cos(\theta) dX - K_N u_N (cos(\alpha)\frac{L}{2} cos(\theta) - sin(\alpha)\frac{L}{2} sin(\theta)) - K_\tau(u_\tau - x_\tau)(sin(\alpha)\frac{L}{2} cos(\theta) + cos(\alpha) \cdot \frac{L}{2} sin(\theta))$$

With:

$$U_N = ucos(\alpha) - vsin(\alpha) + \theta\frac{L}{2}cos(\alpha)$$

$$U_\tau = usin(\alpha) + vcos(\alpha) + \theta\frac{L}{2}sin(\alpha)$$

$$F_r = \begin{cases} \mu_d N & if \quad \dot{u}_\tau > 0 \\ \in [-\mu_s N, \mu_s N] & if \quad \dot{u}_\tau = 0 \\ -\mu_d N & if \quad \dot{u}_\tau < 0 \end{cases}$$

## Modeling

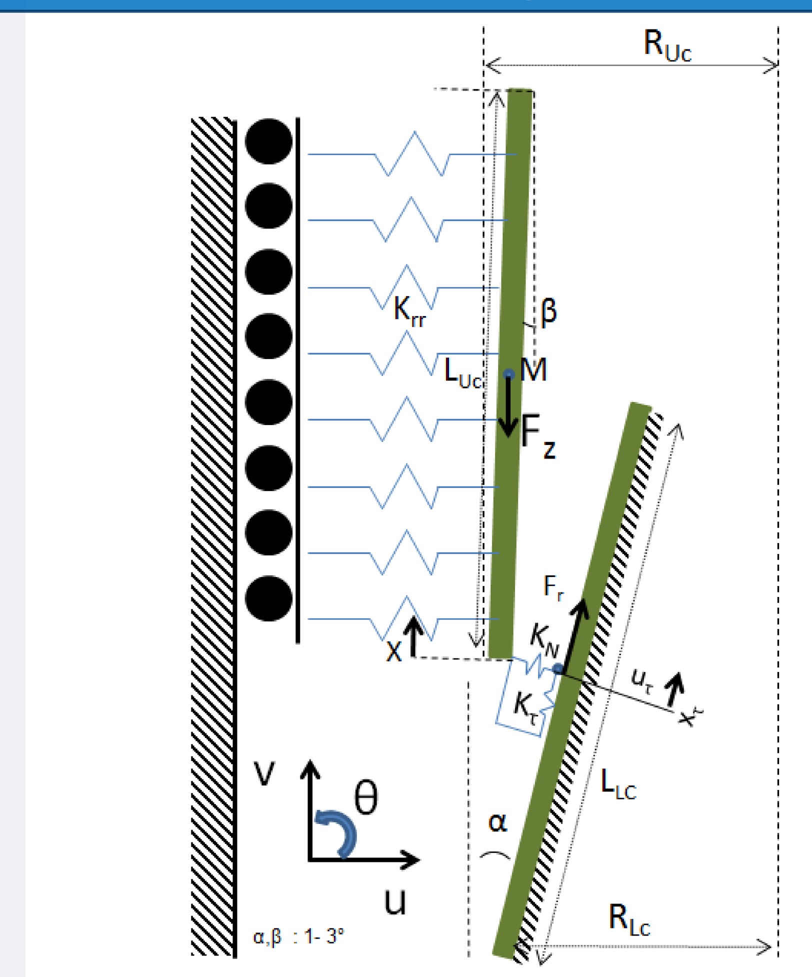



Figure 4: The 1-D model

## Results installation simulations

The settlement of the cone for self weight installation is done for the 5 cases listed in table 1. For all cases the lower cone radius ($R_{LC}$) is 2m. Additionally, case 1 was also done with a initial velocity of 1.4m, which is an velocity equal to a drop of 10cm. This leads to a slight increase in the settlement.

| Case | α/β [°] | μ[-] | $R_{uc}$ [m] |
|---|---|---|---|
| 1 | 2.5/1.5 | 0.4 | 1.89 |
| 2 | 2.5/2.4 | 0.4 | 1.89 |
| 3 | 1.1/1.0 | 0.4 | 1.99 |
| 4 | 1.1/1.0 | 0.3 | 1.99 |
| 5 | 1.1/1.0 | 0.2 | 1.99 |

Table1: Five cases for the settlement under own weight.

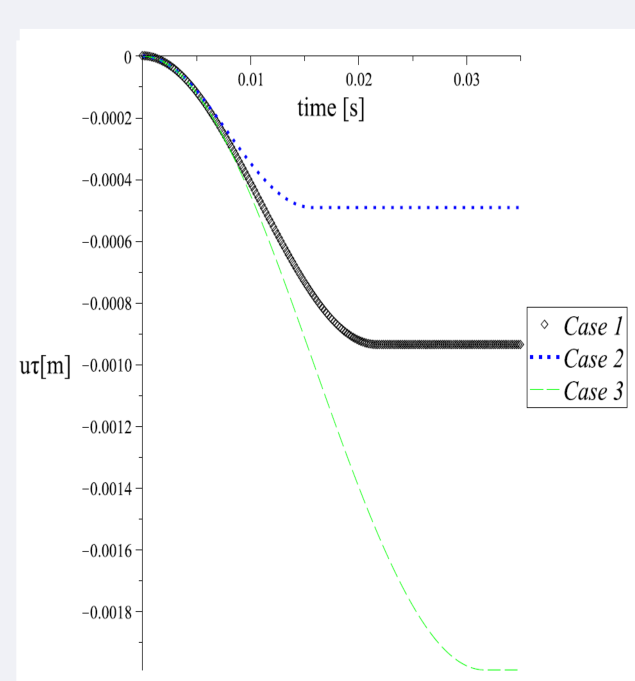



Figure 5: Results of case 1 to 3 of table1

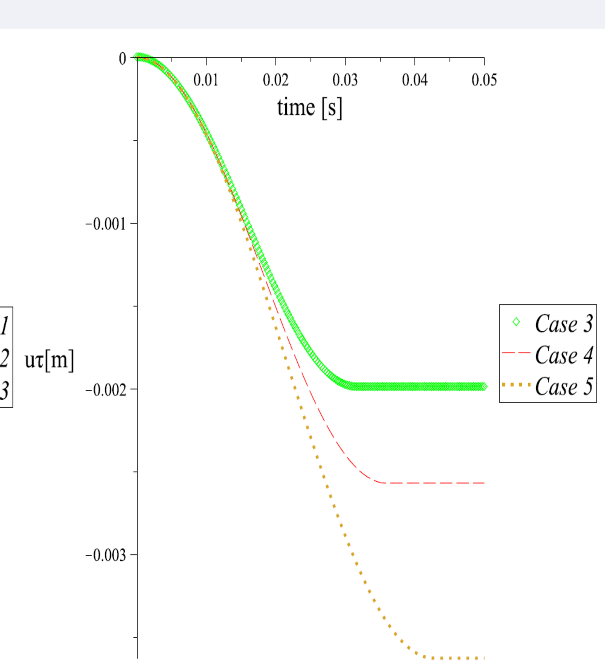
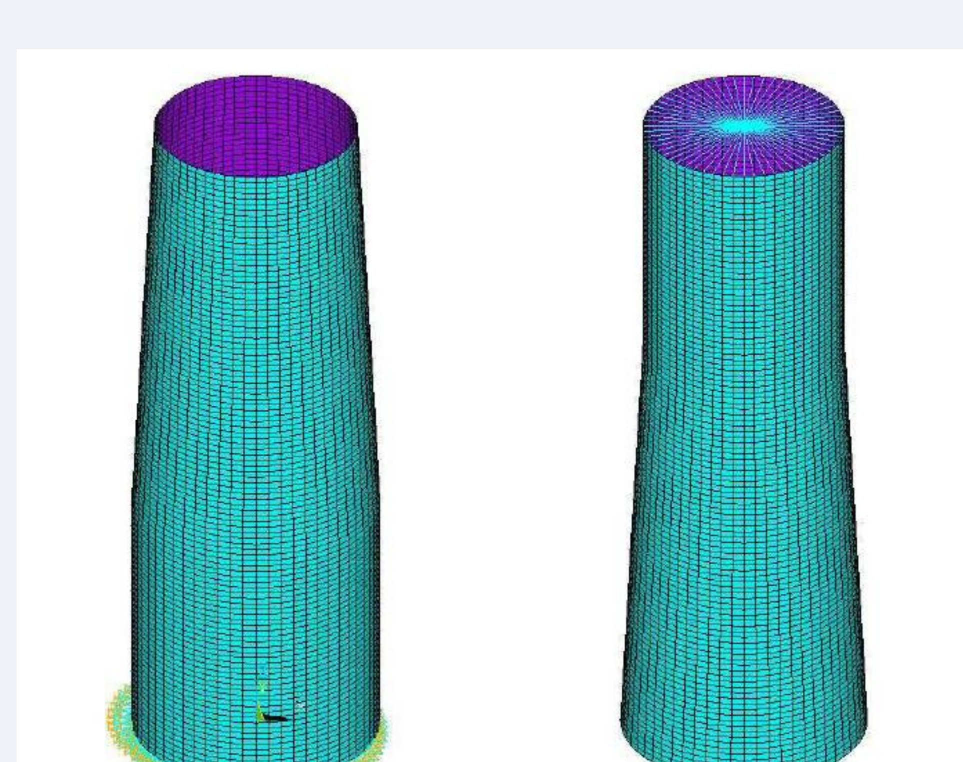



Figure 6: Results of case 3 to 5 of table1

## 2 Finite element modeling

Figure 7 shows the two parts of a representative slip joint as these were modeled in ANSYS. The walls of the monopile and transition piece were modeled using 8-node, 2nd order SHELL281 elements having 6 degrees of freedom at each node. At the base, the monopile is considered to be clamped.

The contact between the monopile and the transition piece is modeled using a surface-to-surface contact model set up by overlaying the conical parts of the assembly with 8-node contact elements (CONTA174).



a) b)

Figure 7: Finite element model of the slip joint a) the monopile b) the transition piece

## Results FE static capacity

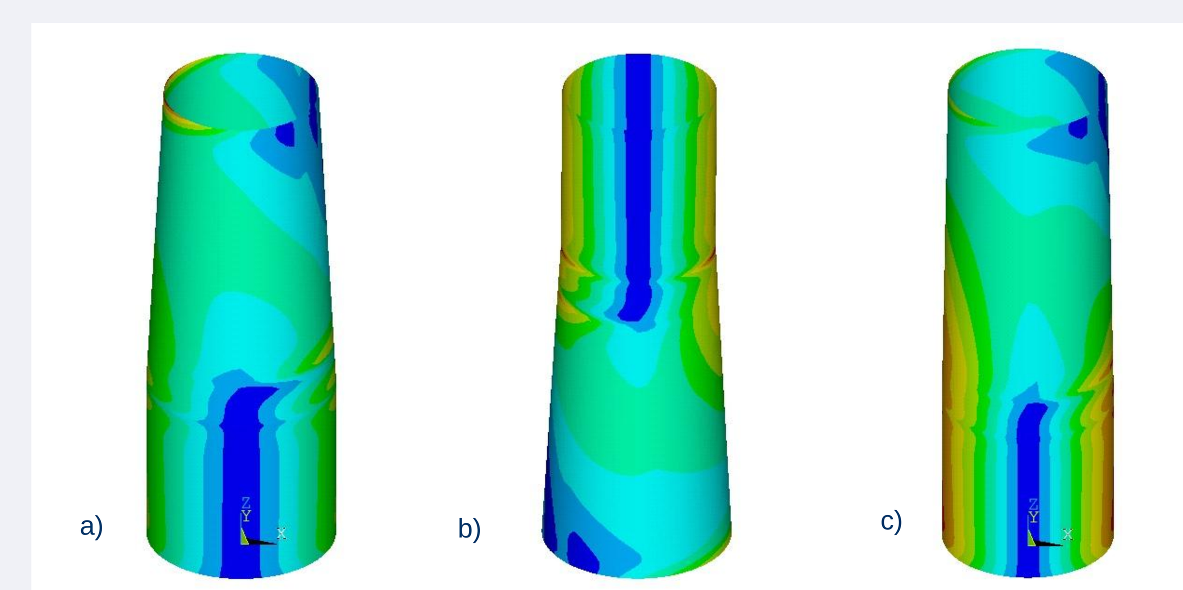
The response of the slip joint to the following two static load cases (LC) was analyzed:

- LC1: Axial load of 2MN.
- LC2: Bending moment of 60MNm & shear force of 1MN.

The effect of the cone angle, friction coefficient , size of the contact area, diameter and wall thickness is analyzed by 24 different cases given in table 2.

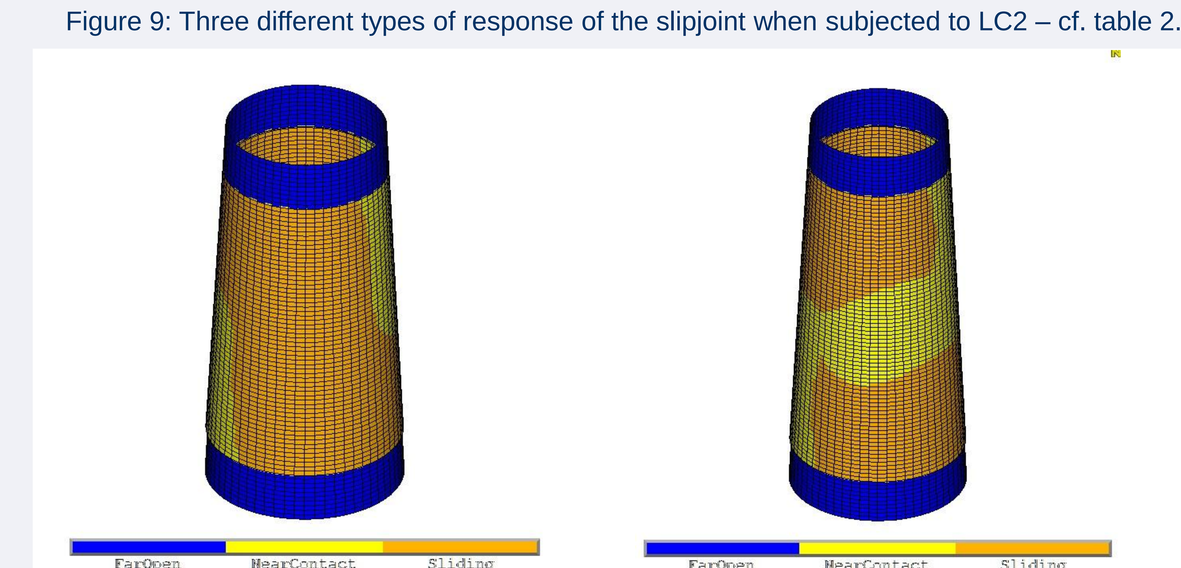
| | | | | | | LC1 | | LC2 | |
|---|---|---|---|---|---|---|---|---|---|
| Set nr. | angle [°] | D [m] | $\mu$ | overlap | $t$ [mm] | $s$ [mm] | $\sigma_{vm}^{max}$ [MPa] | $p_{max}$ [Mpa] | response type |
| 1 | 3 | 4 | 0.2 | 1.2D | 40 | 2.51 | 366.21 | 12.16 | a |
| 2 | 3 | 4 | 0.4 | 1.2D | 40 | 1.54 | 287.94 | 9.61 | a |
| 3 | 3 | 4 | 0.8 | 1.2D | 40 | 0.97 | 227.43 | 6.94 | b |
| 4 | 3 | 4 | 0.2 | 1.5D | 40 | 2,08 | 266.71 | 8.93 | a |
| 5 | 3 | 4 | 0.4 | 1.5D | 40 | 1.31 | 246.15 | 7.30 | b |
| 6 | 3 | 4 | 0.8 | 1.5D | 40 | 0.86 | 245.3 | 5.52 | b |
| 7 | 3 | 4 | 0.2 | 1.8D | 40 | 1.78 | 266.44 | 7.50 | b |
| 8 | 3 | 4 | 0.4 | 1.8D | 40 | 1.15 | 265.69 | 6.34 | b |
| 9 | 3 | 4 | 0.8 | 1.8D | 40 | 0.79 | 264.60 | 4.98 | b |
| 10 | 1 | 4 | 0.2 | 1.2D | 40 | 8.49 | 331.77 | 10.60 | a |
| 11 | 1 | 4 | 0.4 | 1.2D | 40 | 4.58 | 263.97 | 8.46 | a |
| 12 | 1 | 4 | 0.8 | 1.2D | 40 | 2.52 | 190.05 | 6.09 | a |
| 13 | 1 | 4 | 0.2 | 1.5D | 40 | - | 234.25 | 7.28 | a |
| 14 | 1 | 4 | 0.4 | 1.5D | 40 | 3.76 | 191.90 | 5.97 | a |
| 15 | 1 | 4 | 0.8 | 1.5D | 40 | 2.12 | 164.45 | 4.48 | c |
| 16 | 1 | 4 | 0.2 | 1.8D | 40 | 5.78 | 185.37 | 5.74 | a |
| 17 | 1 | 4 | 0.4 | 1.8D | 40 | 3.19 | 167.46 | 4.83 | c |
| 18 | 1 | 4 | 0.8 | 1.8D | 40 | 1.85 | 167.63 | 3.75 | c |
| 19 | 3 | 5 | 0.2 | 1.5D | 40 | 2.05 | 173 | 4.99 | a |
| 20 | 3 | 5 | 0.4 | 1.5D | 40 | 1.28 | 157.29 | 4.08 | b |
| 21 | 3 | 5 | 0.8 | 1.5D | 40 | 0.83 | 156.75 | 3.08 | b |
| 22 | 3 | 4 | 0.2 | 1.5D | 60 | 1.41 | 171.94 | 8.29 | a |
| 23 | 3 | 4 | 0.4 | 1.5D | 60 | 0.88 | 155.59 | 6.79 | b |
| 24 | 3 | 4 | 0.8 | 1.5D | 60 | 0.58 | 154.86 | 5.13 | b |

Table 2: Settlement (LC1), maximum Von Mises stress (LC2), maximum contact pressure $p_{max}$ (LC2) and response type (LC2) for slipjoints having different geometrical and frictional properties



a) b) c)

Figure 9: Three different types of response of the slipjoint when subjected to LC2 – cf. table 2.




a) b)

Figure 10: Two contact status for LC2 for cone angle of 3°, μ =0.4,a) overlap 1.5D b) overlap1.8D

## Conclusions

1. From the dynamic installation analysis it is concluded that even for small initial cone angles, small angle differences between the top and bottom cone, and low friction coefficients, the tangential displacement caused by the self weight is insufficient to come to a desired contact overlap. Future research will focus on the use of applied harmonic forces as well as the influence of additional weight on the installation.
2. During the contact analyses with the FE model, small cone angles and large overlaps were identified as most conducive to a successful transferral of the loads from the transition piece to the monopile. Given the uncertainty on the friction coefficient, it is then recommended to use a cone angle of 1°and preferably an overlap > 1.5D. For final design recommendations, however, a complementary dynamic assessment is necessary.

## References

1. Van der Tempel & Schipholt, *The Slip-Joint Connection, Alternative connection between pile and tower*, DOWEC report, 2003.
2. J.P. Den Hartog, *Forced vibrations with combined viscous and Coulomb damping*,Transactions of American Society of Mechanical Engineers 53, 1931.
3. K. Popp, *Non-Smooth Mechanical Systems – An Overview*, Forchung im Engenieurwesen 64, pp.223-229, Springer, 1998.
4. H. Hong & C. Lui, *Coulomb friction oscillator: Modeling and responses to harmonic loads and base excitations*, Journal of Sound and Vibration 229, 2000.