Electronic supplementary materials

For https://doi.org/10.1631/jzus.A2300243

Influence of overhanging tool length and vibrator material on electromechanical impedance and amplitude prediction in ultrasonic spindle vibrator

Rendi KURNIAWAN[1], Moran XU[1], Min Ki CHOO[1], Shuo CHEN[1], Yein KWAK[1], Jielin CHEN[1], Saood ALI[1], Hanwei TENG[1], Pil Wan HAN[2✉], Gi Soo KIM[3], Tae Jo KO[1✉]

[1]Precision Machining Laboratory, Department of Mechanical Engineering, Yeungnam University, Gyeongsan-si, Gyeongbuk-do, Republic of Korea
[2]Korea Electrotechnology Research Institute (KERI), Changwon-si, Gyeongsangnam-do, Republic of Korea
[3]KASWIN Co., Ltd, Changwon-si, Gyeongsangnam-do, Republic of Korea

S1

The total impedance equation for the left side is expressed as Eq. (9), Z_L^{BM1} and Z^{BM2} can be described in Eqs. (S1) and (S2), respectively. Z_L^{BM} is the total impedance for the left side of the back mass with the screw bolt inside. Z^{BM2} is the impedance of the head bolt.

$$Z_L^{BM} = Z_R^{BM3} + Z_R^{BM1} + \left\{\frac{\left(Z_M^{BM1}+Z_M^{BM3}\right)\times\left(Z_L^{BM1}+Z_L^{BM3}+Z^{BM2}\right)}{\left(Z_M^{BM1}+Z_M^{BM3}\right)+\left(Z_L^{BM1}+Z_L^{BM3}+Z^{BM2}\right)}\right\} \quad \text{(S1)}$$

$$Z^{BM2} = Z_R^{BM2} + \left\{\frac{\left(Z_L^{BM2}\times Z_M^{BM2}\right)}{\left(Z_L^{BM2}+Z_M^{BM2}\right)}\right\} \quad \text{(S2)}$$

The total impedance equation for the right side is introduced in Eq. (10). Z_{F1}, Z^{F2}, Z^H, Z^{SH1}, Z^C, and Z^Tcan be described by Eqs. (S3)–(S8), respectively. Z_{F1} is the total impedance for the flange section 1, Z^{F2} is the total impedance for flange section 2, Z^H is the total impedance for the radius horn, Z^{SH1} is the total impedance for the step horn, Z^C is the total impedance for the combination of nut (N), step horn (SH), collet (C), and entered tool (T1), Z^T is the total impedance for the overhanging tool. Here, B_1, B_2, and B_3 are the label for the screw bolt that entered the horn, flange section 2, and flange section 1, respectively.

$$Z_{F1} = Z_L^{B3} + Z_L^{F1} + \left\{\frac{\left(Z_M^{F1}+Z_M^{B3}\right)\times\left(Z_R^{F1}+Z_R^{B3}+Z^{F2}\right)}{\left(Z_M^{F1}+Z_M^{B3}\right)+\left(Z_R^{F1}+Z_R^{B3}+Z^{F2}\right)}\right\} \quad \text{(S3)}$$

$$Z^{F2} = Z_L^{B2} + Z_L^{F2} + \left\{\frac{\left(Z_M^{F2}+Z_M^{B2}\right)\times\left(Z_R^{F2}+Z_R^{B2}+Z^{H}\right)}{\left(Z_M^{F2}+Z_M^{B2}\right)+\left(Z_R^{F2}+Z_R^{B2}+Z^{H}\right)}\right\} \quad \text{(S4)}$$

$$Z^{H} = Z_L^{B1} + Z_L^{H} + \left\{\frac{\left(Z_M^{H}+Z_M^{B1}\right)\times\left(Z_R^{H}+Z_R^{B1}+Z^{SH1}\right)}{\left(Z_M^{H}+Z_M^{B1}\right)+\left(Z_R^{H}+Z_R^{B1}+Z^{SH1}\right)}\right\} \quad \text{(S5)}$$

$$Z^{SH1} = Z_L^{T2} + Z_L^{SH1} + \left\{\frac{\left(Z_M^{SH1}+Z_M^{T2}\right)\times\left(Z_R^{SH1}+Z_R^{T2}+Z^{C}\right)}{\left(Z_M^{SH1}+Z_M^{T2}\right)+\left(Z_R^{SH1}+Z_R^{T2}+Z^{C}\right)}\right\} \quad \text{(S6)}$$

$$Z^{C} = Z_L^{N} + Z_L^{SH} + Z_L^{C} + Z_L^{T1} + \left\{\frac{\left(Z_L^{N}+Z_M^{SH}+Z_M^{C}+Z_M^{T1}\right)\times\left(Z_L^{N}+Z_R^{SH}+Z_R^{C}+Z^{T}\right)}{\left(Z_R^{N}+Z_M^{SH}+Z_M^{C}+Z_M^{T1}\right)+\left(Z_R^{N}+Z_R^{SH}+Z_R^{C}+Z^{T}\right)}\right\} \quad \text{(S7)}$$

$$Z^{T} = Z_L^{T} + \left\{\frac{Z_M^{T}\times Z_R^{T}}{Z_M^{T}+Z_R^{T}}\right\} \quad \text{(S8)}$$

<u>Charge constant:</u>

$$\boldsymbol{d} = \begin{bmatrix} 0 & 0 & 0 & 0 & 4.96 & 0 \\ 0 & 0 & 0 & 4.96 & 0 & 0 \\ -1.23 & -1.23 & 2.9 & 0 & 0 & 0 \end{bmatrix} \times 10^{-10} \ \ \mathrm{M/V} \quad \text{(S9)}$$

Compliance:

$$\boldsymbol{C}^{E} = \begin{bmatrix} 13.9 & 7.8 & 7.4 & 0 & 0 & 0 \\ 7.8 & 13.9 & 7.4 & 0 & 0 & 0 \\ 7.4 & 7.4 & 1.15 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.56 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.56 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3.05 \end{bmatrix} \times 10^{10}\ \mathrm{N/m^2} \quad \text{(S10)}$$

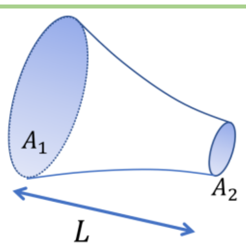
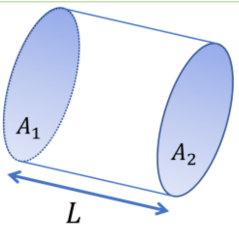
Elastic:

$$\boldsymbol{e} = \begin{bmatrix} 0 & 0 & 0 & 0 & 12.7 & 0 \\ 0 & 0 & 0 & 12.7 & 0 & 0 \\ -5.2 & -5.2 & 15.1 & 0 & 0 & 0 \end{bmatrix}\ \mathrm{C/m^2} \quad \text{(S11)}$$

Strain:

$$\boldsymbol{\epsilon}^{T} = \begin{bmatrix} 6.5 & 0 & 0 \\ 0 & 6.5 & 0 \\ 0 & 0 & 5.6 \end{bmatrix} \times 10^{-9}\ C/Vm \quad \text{(S12)}$$

Table S1 Acoustic Impedance of the solid structure for different shapes (Zhang et al., 2019)

Type	Diagram	Parameter	Equation
Exponential Shape		$A_2 = A_1 e^{-2\beta L}$ $\tau_1 = \sqrt{\tau^2 - \beta^2}$ A_1 and A_2 are the first and second areas of the cross-section. L is the total horn length	$Z_M^i = \left(\frac{\tau_1}{\tau}\right)\frac{\rho \cdot c\sqrt{A_1 A_2}}{j \cdot \sin(\tau_1 L)}$ $Z_L^i = \rho \cdot c \cdot A_1 \left(\frac{\tau_1}{\tau}\frac{1}{j \cdot \tan(\tau_1 L)} - \frac{\beta}{j \cdot \tau}\right) - \frac{\tau_1}{\tau}\frac{\rho \cdot c\sqrt{A_1 A_2}}{j \cdot \sin(\tau_1 L)}$ $Z_R^i = \rho \cdot c \cdot A_2 \left(\frac{\tau_1}{\tau}\frac{1}{j \cdot \tan(\tau_1 L)} + \frac{\beta}{j \cdot \tau}\right) - \frac{\tau_1}{\tau}\frac{\rho \cdot c\sqrt{A_1 A_2}}{j \cdot \sin(\tau_1 L)}$
Cylindrical Shape		$A_1 = A_2 = A$ A_1 and A_2 are the first and second areas of the cross-section. L is the total horn length	$Z_M^i = \frac{\rho \cdot c \cdot A}{j \cdot \sin(\tau L)}$ $Z_L^i = Z_R^i = \rho \cdot c \cdot A \left(\frac{1}{j \cdot \tan(\tau L)} - \frac{1}{j \cdot \tan(\tau L)}\right)$

Z_{M}^{i} indicates the acoustic impedance in the middle position for the T-shape impedance structure; Z_{L}^{i} and Z_{R}^{i} are the left and right acoustic impedances for a T-shaped impedance structure, respectively.

Based on the data graphed in Fig. 6, the exponential equation is ($y = 7.107\mathrm{e}^{-0.4999x}$); thus the β value for Table S1 is an exponential constant of $\beta \approx {}^{0.4999}/_{2} \approx 0.25$.