연 구 논 문

저항점 용접에서 전극팽창에 관한 동적모델

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Dynamic Model for Electrode Expansion in Resistance Spot Welding Machines

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Abstract

A lumped mass damped vibratory model was proposed for quantitative understanding of welding machine characteristics. An experimental setup was developed to determine the mechanical parameters (moving mass m, equivalent stiffness k and damping c) which govern the dynamic mechanical response of the resistance spot welding machine. During the test, acceleration of the electrodes for each level of applied load was measured by accelerometer, filtered and numerically integrated to find the corresponding velocity and displacement. The machine dynamic parameters were determined by finding the unknowns of the proposed model with experimental data.

A Simulink model was proposed to investigate the influence of these mechanical parameters on the welding process. The electrode response was simulated by changing values of stiffness and damping. It was observed that both of the machine parameters(c, k) have significant effect on the response of electrode head.

Key Words: Resistance spot welding, Electrode head movement, Accelerometer, Welding machine dynamics

1. Introduction

Resistance spot welding (RSW) is one of the most productive joining methods, in which weld joint is formed between two sheet metals by Joule heating. When the welding current is passed through the faying interface, the material around the contact point will be molten and gradually form a nugget. The nugget then solidifies on cooling and forms a joint spot.

New inventions and innovative developments in recent years have revitalized the technology of resistance welding and have enabled new possibilities for joining challenging materials such as aluminum, magnesium and advanced high strength steels. These advances have drawn greater attention from manufacturers towards new applications of resistance welding techniques. With extensive research and development by material suppliers, welding equipment manufacturers and industrial end users, it is obvious to see that resistance welding remains one of the most efficient and competitive joining technology in automotive, aerospace, electrical, electronics, home appliances and other metal processing industries[1-4].

Resistance spot welding (RSW) system consists of two systems: electrical system and mechanical system. Both systems have effect on the weld quality. Researchers believe that the process signatures such as dynamic resistance, electrode movement, electrode force and other process characteristics provide important information for RSW processes[5-8]. Electrode movement has been proven to be the best indicator of nugget initiation and growth. An analysis of this signature can potentially yield valuable information about the size and strength of the nugget. Since this process signature is also a mechanical response of RSW machine during welding, spot weld quality is partly dependent upon mechanical characteristics of RSW machine as well as weld condition. Hence, mechanical characteristics of RSW machines must have complicated influence on the resistance welding process and weld quality. Experimental and analytical studies were performed to understand such influences. It has been found that the damping and stiffness have more effect in comparison to the moving mass[9]. Therefore, more work is needed to find the exact numerical values of stiffness and damping as well as moving mass. In view of the fact that RSW includes complicated thermo-physical process, this is a challenging task. Moreover, the complexity of the machine structure makes it very difficult to measure actual mechanical parameters.

A notable work has been done to characterize the dynamic mechanical parameters of projection welding machine. The independent machine parameters were found experimentally by a free breaking test. A load cell and LVDT sensor were used to find electrode force and corresponding electrode displacement. The unknowns, mechanical parameters of the proposed dynamic model, were solved using calculated velocity and acceleration together with measured displacement data[10]. In this work, numerical differentiation of displacement with respect to time was attempted so as to obtain velocity and acceleration. However, this method is susceptible to strong electromagnetic noise in RSW machine, thus not free from considerable errors in numerical computation.

Another analytical model was developed for the machine response, in which electrode force is input and electrode displacement is output. The machine characteristic parameters were found by tracking the electrode movement using a high speed camera. Correlation by empirical model was found between dynamic force and electrode movement using curve fitting method[11]. Since this model was derived by polynomial fitting and static input-output relation, dynamic information could not be included in this model.

In this work, a lumped-mass damped vibratory one DOF (degree of freedom) model was proposed for quantitative understanding of RSW machine characteristics. The electrode force is input and the electrode head displacement is output of the model. An experimental setup was developed to determine the mechanical parameters (moving mass m, equivalent stiffness k and damping c) which govern the dynamic mechanical response of the RSW machine. During the experiment, acceleration of the electrodes for each level of applied load was measured by accelerometer. The analog output was filtered and numerically integrated to calculate corresponding velocity and displacement. The machine dynamic parameters were determined by finding the unknowns of the proposed model with experimental data.

A Simulink model was proposed to investigate influence of these mechanical parameters on RSW machine dynamic behavior. The electrode response was simulated by changing the values of stiffness and damping to predict the effect of each parameter and its combined effect.

2. Welding Machine Modeling and Experiment

The dynamic mechanical parameters of RSW machine such as moving mass m, damping c and stiffness k have been recognized to have significant influences on weld quality. Recently, researchers have made valuable contributions to the understanding of the effects of the machine characteristics on welding[5-11]. However, previous results were mostly descriptive and based on qualitative reasoning. Further work is needed to find out explicit expression for the influence of characteristic mechanical parameters (m, c and k) on the weld quality. Due to the complexity of the machine, it is a challenging process to find the exact value of equivalent m, c and k. Once we find the equivalent m, c and k, further investigation for quantitative analysis of each parameter's effect on the welding process will be straightforward.

2.1 Dynamic model

The upper and lower electrodes together with their holders and associated actuation to the structural components of the machine are modeled by one degree of freedom (DOF) system that incorporates spring, damper and mass elements.

The machine used for experiments is a servo-actuated spot welding machine. The side view of the machine is shown in Fig. 1. The mass of the moving parts associated with the upper electrode, its holder and the driving mechanism are combined into one lumped mass. Similarly, the stiffness and damping elements represent the corresponding effective properties of all the moving parts. Equivalent dynamic model is shown in Fig. 2.

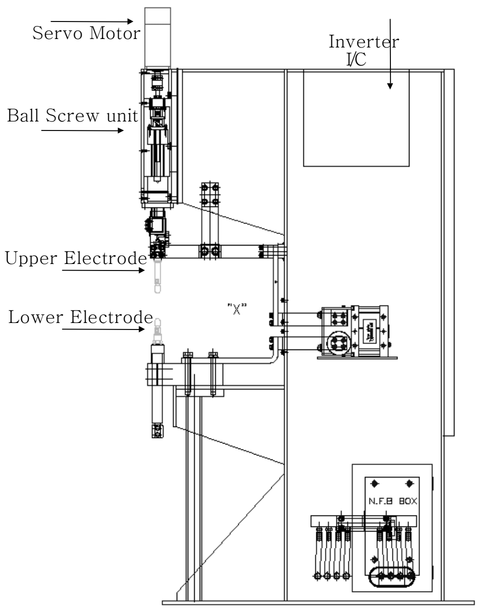


Fig. 1 Servo-actuated resistance spot welding machine

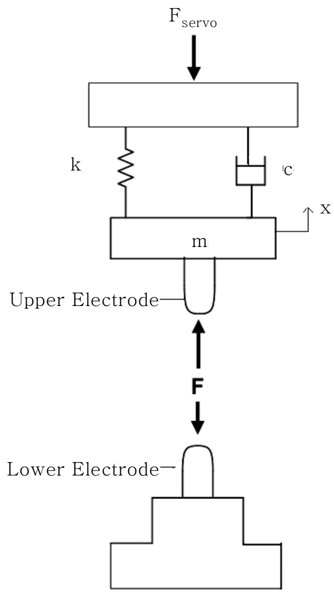


Fig. 2 Equivalent dynamic model for resistance spot welding machine

The details of the thermo-physical process (such as heating, expansion and melting) are not considered in this model. Instead, the contribution of the welding process to the electrode forces and displacements is taken into account by a pair of forces exerted on both the upper and the lower electrodes. The relative movement between two electrodes can be described by the following equation;

$$m\ddot{x} + c\dot{x} + kx = F \tag{1}$$

where F is the total force applied by electrode and x is electrode movement.

To set up the mathematical model above, machine parameters (m, c, and k) need to be determined. Series of experiments were performed to find these unknowns of the equation (1).

2.2 Experiment

A displacement sensor is usually used to measure electrode motion along its axial direction for monitoring of electrode head. However, for some welding systems, the lateral stiffness in a direction perpendicular to the electrode axis is also a concern, as angular misalignment may be induced in that direction, especially under large electrode forces. To solve this problem, either a special fixture needs to be designed or multi sensors have to be used to secure proper gap between sensor and target object. Another problem associated with displacement sensor is its limitations in sensitivity in measuring the wide range of electrode displacement. To avoid this problem, appropriate accelerometer was used in view of its advantage over displacement sensor. Accelerometer can pick up any acceleration of the object on which it is mounted. It is free from spatial requirements needed for precise measurement.

Loading experiments were carried out in a special test setup. The tests were performed on a servo-actuated welding machine. Test setup is schematically shown in Fig. 3. The lower electrode was replaced by a solid cylinder and a load cell was bolted with it. A load support structure, with a steel plate (10cm × 7cm × 1.2cm) placed on the top, was mounted on the solid cylinder-load cell assembly. To avoid tilting, ball bearing was installed. Lower part of the support structure was free so that all the force applied by upper electrode is transferred and sensed by the load cell. A fixture was attached firmly to the upper electrode so as to install accelerometer (high sensitivity, quartz

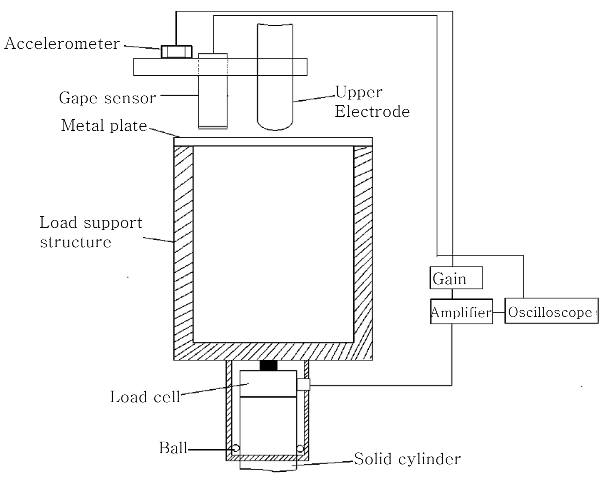


Fig. 3 Experimental setup

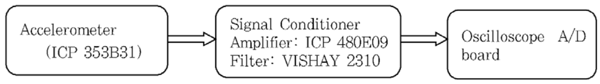


Fig. 4 Accelerometer data acquisition system

shear ICP® 353B31, 50 mV/g, 1 to 5k Hz) and gap sensor (Ono-Sokki VS 021: eddy current type, F.S. output 0~10V at distance to target 0~2 mm). The accelerometer measured the acceleration of the upper electrode, while the gap sensor detected the gap between the sensor and the metal plate, i.e., electrode displacement (x).

During the test, acceleration $\ddot{x}$ was measured by accelerometer for each applied load. The total action force F was measured by load cell mounted on solid cylinder. The measurements were recorded on digital storage device. The accelerometer data acquisition system is shown in Fig. 4.

The noise in accelerometer signal was filtered out using an analog signal conditioning unit (VISHAY 2310), a Butterworth filter with 30 Hz cut off frequency. The filtered signal, as shown in Fig. 6, was numerically integrated once to get $\dot{x}$ (velocity) and twice to get x (displacement) values. To check validity of this signal processing system, calculated displacement values were compared with the actual displacement values measured by the gap sensor.

Using data acquired in n sets of measurement, Equation (1) can be numerically denoted in matrix form as follows[9];

$$\begin{Bmatrix} \ddot{x}_1 & \dot{x}_1 & x_1 \\ \ddot{x}_2 & \dot{x}_2 & x_2 \\ \vdots & \vdots & \vdots \\ \ddot{x}_n & \dot{x}_n & x_n \end{Bmatrix} \begin{Bmatrix} m \\ c \\ k \end{Bmatrix} = \begin{Bmatrix} F_1 \\ F_2 \\ \vdots \\ F_n \end{Bmatrix} \quad (2)$$

For each calculation, n corresponding values of $\ddot{x}$, $\dot{x}$ and x with applied force F were inserted into the Equation (2). The machine dynamic mechanical parameters m, c and k were determined by solving the n equations using the least-squares method in MATLAB. Tests were carried out with four loads (100, 150, 200 and 250 kgf).

2.3 Simulink model

A Simulink model was proposed so as to simulate electrode movement (displacement) for various values of electrode force. In the previous section 2.2, dynamic model denoted by the Equation (1) was identified by calculating the numerical values of *m, c* and *k.*

$$m\ddot{x} + c\dot{x} + kx = F \qquad (1)$$

By simple rearrangement, the electrode displacement can be simply calculated by;

$$x = \iint 1/m\,[F - c\dot{x} - kx]\; dtdt \qquad (3)$$

Using this Equation (3), the equivalent Simulink model for this one DOF is described in Fig. 5.

To investigate the influence of mechanical parameters (*m, c* and *k*) on the welding process, the electrode movement was simulated by changing the values of equivalent mass, stiffness and damping parameters.

3. Results and Discussion

3.1 Signal Processing

The electrode force was applied by servo-actuated head. Immediately after the start of downward electrode movement, a slight jerky motion caused initial swing of the acceleration. Until contact, measured values showed machine structural vibration due to ball screw rotation. When the upper electrode touched the steel plate (in Fig. 3) at the time of 1250 ms, remarkable value of acceleration was measured as shown in Fig. 6. Power spectrum of the acceleration signal in Fig. 7 indicates that it has rich contents below 40 Hz. These peaks in the spectrum reflect that structural characteristics of electrode system in RSW machine have inherently low frequency range of primary vibration mode. Due to lots of sharp high frequency noise superimposed on acceleration signal, raw data needs low pass filtering. Low-pass-filtered data was also plotted by bold solid line in Fig. 6.

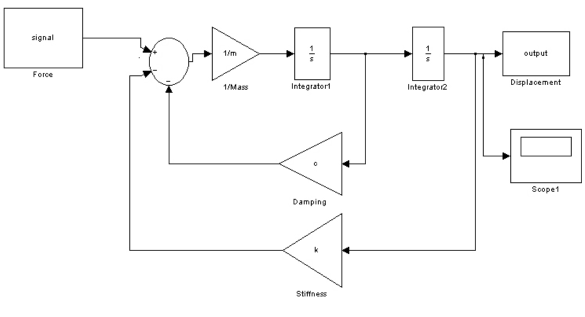


Fig. 5 Simulink model for welding machine dynamics

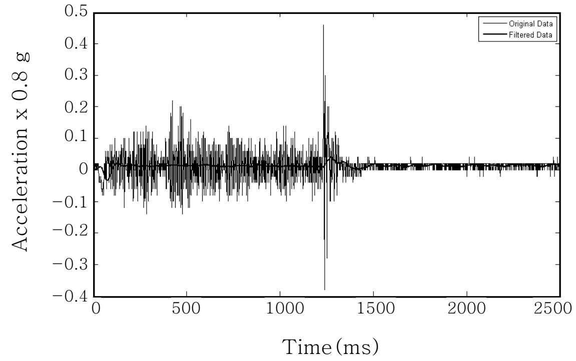


Fig. 6 Original and filtered accelerometer signal output

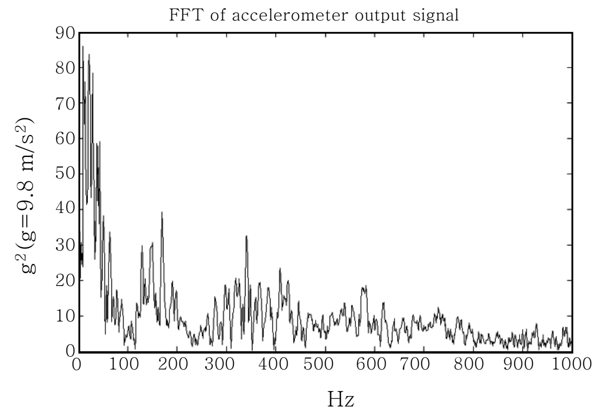
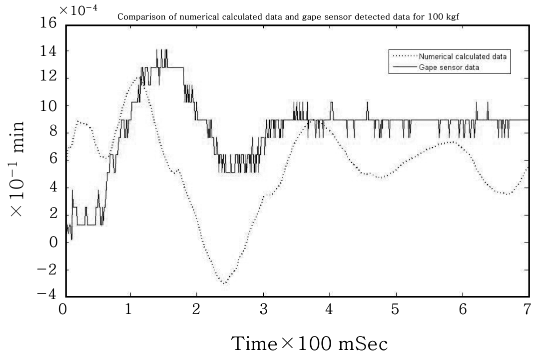
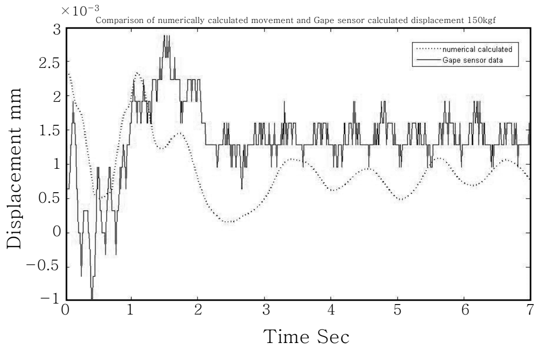


Fig. 7 Power spectrum of accelerometer output

To check validity of this numerical integration system, raw displacement data measured by gap sensor was compared with x, numerically double integrated data. Fig. 8 shows agreement between the two data. In Fig. 8(a), peak value of vibration is around 1.2×10^{-3} mm. Good match can be observed in two wave forms except slight phase delay and mismatch due to poor resolution of gap sensor. In Fig. 8(b),



(a) Electrode force = 100 kgf



(b) Electrode force = 150 kgf

Fig. 8 Comparison of double integrated data to gap sensor data

better match can be found due to higher signal level and peak value of 2.5×10^{-3} mm. It is notable that both double integrated signal (electrode displacement) and gap sensor output show typical damped vibratory response to step input force (150 kgf). The damping phenomenon was accounted for the friction between various machine couplings and parts and in the servo head as well.

3.2 Mechanical Parameters of Dynamic Model

Various forces were applied once in every test and resulting responses were sampled. Filtered acceleration signal was numerically integrated once and twice to solve the proposed dynamic model using the equation (2). The characteristic mechanical parameters *(m, c* and *k)* were calculated for four different force values. Once these parameters were calculated, another set of experiments were conducted again to check repeatability of the calculated parameter values.

The values of equivalent mass of RSW machine are plotted in Fig. 9. As shown in Fig.

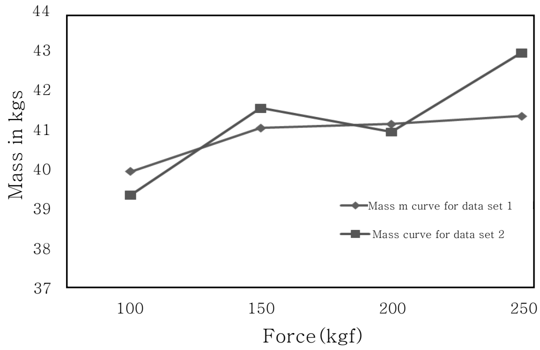


Fig. 9 Equivalent mass (m) of dynamic model

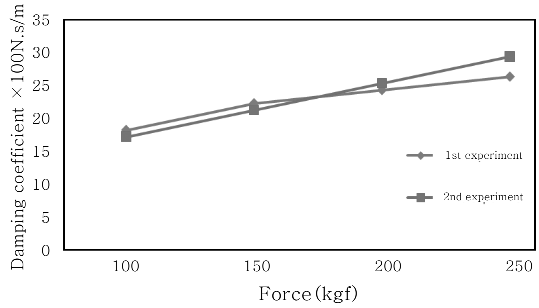


Fig. 10 Equivalent damping coefficient (c) of dynamic model

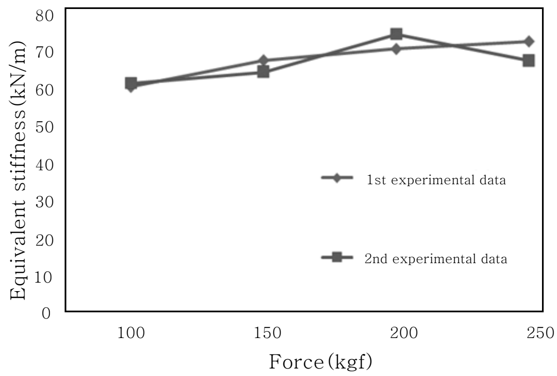


Fig. 11 Equivalent stiffness (k) of dynamic model

9, numerical values of equivalent mass were found between 39.5 kg and 43 kg, indicating fairly good consistency. The equivalent damping coefficient and stiffness are shown in Fig. 10 and Fig. 11, respectively. In Fig. 10, linear trend with increasing force was found in the equivalent damping coefficient. This error associated with trend can be attributable to the fact that effective damping is determined by resultant action of unstable friction occurring on every contact. On the other hand, calculated equivalent stiffness values were found to be nearly constant as shown in Fig. 11.

Even though some errors were found per each set of experiment and calculation, notable consistencies can be found in the numerical values of mechanical parameters. Some discrepancies between calculated numerical values are attributable to filtering and numerical integration error. Another reason for error can be the use of simple one DOF linear model.

In view of consistencies shown in the Fig. 9, Fig. 10 and Fig. 11, proposed dynamic model can be used for characterization of RSW machine dynamics. Few attempts have been made to propose this 'closed form dynamic model' i.e., electrode force as input and electrode movement as output for RSW machine.

3.3 Simulation by Simulink Model

The simulink model for the proposed machine dynamics model was utilized to find the effect of each and combined effect of characteristic dynamic parameters on the response. In this model, the electrode force is input and the electrode movement is output. First, to find the effect of individual dynamic parameter (*m*, *c* and *k*) on the response, the values of two parameters among these three were kept constant and the third was changed below and above the range of its experimentally calculated values. The input force wave form was generated so as to simulate the actual force applied during real welding cycle.

Response of the Simulink model showed good agreement with the typical electrode movement curve, which can be observed during welding process with proper weld condition. It was observed that all the machine parameters *m*, *c* and *k* have significant effect on the response of the electrode head. In Fig. 12, increase of mass *m* caused slower response during weld time, which fact is common practice in ordinary mechanical system. In Fig. 13, lower value of damping *c* showed underdamped response. As damping *c* increases, the response changed from underdamped to overdamped response.

A notable variation of response for different values of stiffness was observed in Fig. 14. For higher stiffness *k* value, the amount of total electrode movement was suppressed. However, typical pattern of electrode movement waveforms (during weld time) was observed regardless of stiffness value. The implication of this finding is that we can safely and successfully use most of RSW machine regardless of its physical size as long as we maintain proper weld condition. In case of using larger RSW machine, higher weld current and electrode force are recommended since it has higher stiffness and bigger moving mass.

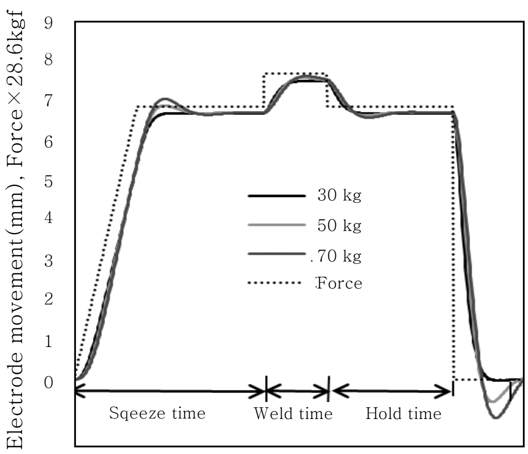


Fig. 12 Dynamic model response for various masses (m)(damping c = 2.5 kN· s/m, stiffness k = 70 kN/m)

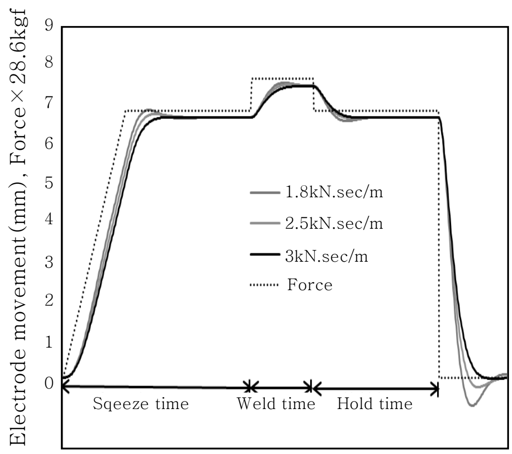


Fig. 13 Dynamic model response for various damping values (c) (mass m =52 kg, stiffness k = 70 kN/m)

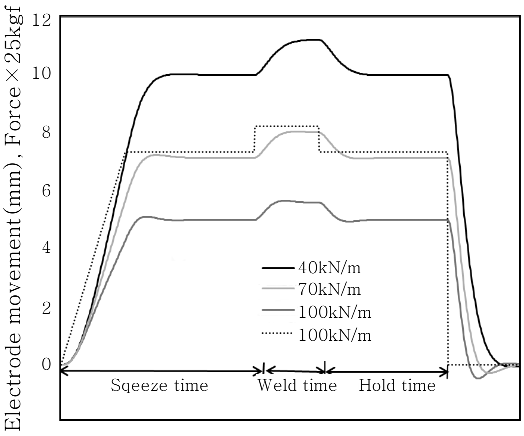


Fig. 14 Dynamic model response for various stiffness level (k)(mass m = 52 kg, damping c = 2.5 kN· s/m)

4. Conclusion

A dynamic model for electrode force and movement was proposed and an experimental setup was designed. Experiments were carried out to determine dynamic mechanical parameters. The equivalent mass *m*, equivalent damping *c* and equivalent stiffness *k* of RSW machine were calculated using the measured data.

A Simulink model was built to check the validity of proposed dynamic model. Response of the Simulink model showed good agreement with the typical electrode movement curve. The effect of each mechanical parameter was found by changing its value while the input force and other parameters were kept the same. The Simulink model was found to be useful in the quantitative understanding of mechanical parameter and its effect on RSW machine characteristics.

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