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Improved Dynamic Characteristics for Machine Tools Structure Using Filler Materials

Harshad Sonawane[a]*, T Subramanian[a]

[a]*Dr. Kalam Center for Innovation, Bharat Fritz Werner Ltd., Off Tumkur Road, Bengaluru 560022, India*

* Corresponding author. Tel.: +91 80 3982 1408; fax: +91 80 3982 1100. *E-mail address:* harshad.s@bfw.co.in

Abstract

Simplified filler approach has been developed to enhance structural stability of existing cast iron columns and beds. The motivation for this research was to develop a machine tool structural material having characteristics such as, improved dynamic stability, ease in production, cost-effectiveness, and sustainability. A methodology has been developed to predict dynamic behaviour of prototype column structure using simplified reduced odd-scale model. A combination of formulae based similitude model, FE based structural analysis and statistics based Taguchi design analysis has been used to achieve enhanced structural dynamic performance of a VMC column. Similitude principles have been developed to correlate simplified odd-scale column model with existing complex prototype column through FE based 1:5 scaled column structure. Prototype column has been replaced by simplified odd-scale column for filler optimization experiments using Taguchi design and scaling factors. Simplified odd-scale column models were filled with a number of combinational designs of unique composite filler material. VMC column structural stability in terms of excitation decay time, dynamic stress and displacement has been analyzed for present hollow cast iron structures as well as filled structures. Present methodology combination reduces efforts to develop dynamically improved machine tool structures through simplified odd-scale models, avoiding complexity involved in implementation of traditional scaling approach. As a result, dynamic characteristics have been improved by 20-30 times with introduction of composite filler material as compared to unfilled structures. This composite filler technology has been applied for patent.

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Keywords: Machine tool; Structural stability; Composite Filler; Stress; Displacement

1. Introduction

Precision machining requires close tolerance machined surface finish as one of the major criteria to be fulfilled. However, the micro- or nano-range surface quality cannot be achieved only through optimum combination of machining parameters. Literature shows that cutting stability is one of the most notorious aspects associated with precision machining [1]. Moreover, most of the research on cutting stability is concentrating on use of stability lobe diagrams (SLDs). However, several major disadvantages have been associated with this approach [2]. Structural stability in a machine tool has been addressed through design modifications, addition of dampers, developing alternative structural materials or filling existing metal structures with innovative filler materials.

A vast variety of machine tool structural materials has been analyzed and has been found in application since early 17th century. Few examples are, metals like steel [3, 4, 5, and 6], cast iron, metal alloys [7, 8], natural materials like, granite [9, 10, and 11] and ceramics [12, 13], advanced materials like, mineral casting [14, 15], extraordinary materials like metal foams [16, 17], fiber reinforced and composite materials [18, 19], and hybrid structures [20, 21].

Researchers used fillers such as sand [22, 23] and closely packed glass balls [24] inside cast iron structures to enhance structural damping. Steel frame structures were filled with ordinary concrete to achieve better dynamic properties [25]. An analogous concept of filling existing cast iron machine tool structures has been developed. The composite material was filled inside hollow space in cast iron column structures.

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In this research paper, three main sections are presented. In the first section, scaling principles have been developed for unfilled prototype column, 1:5 scaled and, simplified odd-scaled models. Simplified odd-scale model was correlated with prototype column with the help of scaling principles through FE analysis and experimental modal analysis. In the next section, series of experiments were performed on simplified odd-scaled models using statistical Taguchi design of experiments to optimize filler design. In the last section, scaling correlation developed in first section for unfilled columns were used to predict performance of filled columns.

Simplified odd-scaled column model was designed and manufactured by imitating overall geometrical appearance of prototype and by neglecting intrinsic structural details such as, column ribs, fillets, holes, etc. Formula-based mathematical models and FE-based 3D structural models were developed to verify similitude principle.

2. Modelling

This section consists of development of formulae based similitude model, 3D FE model, and statistical model for filler design. Scaling factors have been evaluated for unfilled prototype column, 1:5 scale and simplified odd-scale column models using similitude theory. FE based 3D structures for prototype and models have been developed using SolidWorks modeling software. Taguchi design model has been developed for filler material using statistics based Minitab software.

2.1. Mathematical model for similitude

The model can be correlated with prototype for its static and dynamic performance using similarity criteria [8, 9]. Scaling factors can be developed for various parameters using basic dimensional equations. For dynamic analysis, scaling factors for models can be evaluated using basic differential equation of motion. The forced vibration equation for prototype of machine tool column using harmonic force excitation can be represented as,

$$m_p \ddot{x}_p + C_p \dot{x}_p + k_p x_p = F(t)_p \tag{1}$$

After substituting similarity ratios, we get,

$$C_m m_m \frac{d^2(C_x x_m)}{d(C_t t_m)^2} + C_c c \frac{d(C_x x_m)}{d(C_t t_m)} + C_k k_m C_x x_m = C_F F_m(t) \tag{2}$$

Subscripts p and m represent prototype and model, respectively. Similarity constants C_m, C_ρ, C_l, C_x, C_t, and C_E are similarity ratios for mass, density, length/height, displacement, time and modulus of elasticity.

According to similarity theory, similarity ratios in Eq. (2) can be deduced as,

$$\frac{C_\rho C_l^3 C_x}{C_t^2} = \frac{C_c C_x}{C_t} = C_E C_l C_x = C_F \tag{3}$$

Rearranging exponents in above equation, we can correlate similarity constants for displacement (C_x), time (C_t), velocity (C_v), acceleration (C_a), force (C_F), stress (C_σ), stiffness (C_k), dynamic strain (C_ε), damping (C_c) and natural frequency (C_f) with basic constants through Eq. (4-13), respectively.

$$C_x = C_l \tag{4}$$

$$C_t = C_l \sqrt{\frac{C_\rho}{C_E}} \tag{5}$$

$$C_v = \frac{C_x}{C_t} = \sqrt{\frac{C_E}{C_\rho}} \tag{6}$$

$$C_a = \frac{C_v}{C_t} = \frac{C_E}{C_\rho C_l} \tag{7}$$

$$C_F = C_E C_x C_l \tag{8}$$

$$C_\sigma = \frac{C_F}{C_x C_l} = C_E \tag{9}$$

$$C_k = \frac{C_F}{C_x} = C_E C_l \tag{10}$$

$$C_\varepsilon = \frac{C_\sigma}{C_E} = 1 \tag{11}$$

$$C_c = C_E C_l C_t \tag{12}$$

$$C_f = \frac{C_l}{C_v} = C_l \sqrt{C_\rho / C_E} \tag{13}$$

Scaling correlations among different parameters of prototype column and 1:5 scaled models are summarized in Table 1.

Table 1. Similitude for 1:5 scaled model column.

Type of scaling	Ratio for 1:5 scaled model	Type of scaling	Ratio for 1:5 scaled model
Displacement	5	Stress	1
Time	5	Stain	1
Velocity	1	Stiffness	5
Acceleration	0.2	Damping	25
Force	25	Natural frequency	0.2

2.2. FEA model for similitude

The reduced 1:5 scaled column model was obtained from prototype column structure using SolidWorks. A simplified 3D odd-scale column model has been drawn using FE modelling. Typical 3D structures for prototype column, 1:5 scaled and odd-scaled models are shown in Fig. 1.