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Technical note

A new tunable dynamics platform for milling experiments

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ABSTRACT

This paper describes a flexure-based platform with tunable dynamics that is used for milling stability experiments. Damping is added to a parallelogram, leaf-type flexure by incorporating an eddy current damper. Using this flexure/damper combination, the platform dynamics can be selected (tuned) at the design stage to match the desired experimental conditions. An increase in the dimensionless damping ratio of over 200% is demonstrated through the addition of the eddy current damper. The design analysis is detailed and experimental results are presented for modal testing and milling stability trials.

1. Introduction

Time and frequency domain milling process models may be implemented to enable pre-process parameter selection for increased material removal rate, improved surface finish, and enhanced accuracy (see [1–3], for example). To complete these simulations and validate the results, the system dynamics must be known. Typically, the cutting tool flexibility dominates the system dynamics, although the workpiece can introduce significant flexibility in some cases as well.

To realize a validation platform with simple (often single degree of freedom) dynamics, flexures may be used to support the workpiece (see Fig. 1). In this configuration, the flexure stiffness may be selected to be much lower than the tool stiffness so that the tool dynamics can be effectively ignored. One aspect of using flexures is that the damping is low (typically 1% or less). It may be desired, however, to perform milling experiments on a system with increased damping. In this paper, a flexure platform is described which offers an ideal setup for milling process dynamics experiments. It offers stiffness, natural frequency, and viscous damping values that can be tuned using first principles models at the design stage to match the desired frequency response. In this way, structural dynamics can be adjusted to test milling models over a broad range. An example application is machining of the monolithic thin-walled structures that are common in the aerospace industry [4–8].

2. Milling platform concept

The basis for the milling platform designed and tested in this study is a parallelogram, leaf-type flexure. By selecting the leaf geometry and workpiece/platform mass, the stiffness and natural frequency can be defined to meet the experimental requirements. The design approach is described in [9] and, for brevity, is not discussed here. As noted, however, the damping for this geometry, particularly monolithic designs, is low.

To introduce higher damping using a first principles model, the addition of an eddy current damper to the flexure setup is investigated here. The viscous (velocity-dependent) damping force for an eddy current damper can be described analytically. Fig. 2 displays the motion of a conductor[1] relative to a magnet (or magnet pair) with the motion perpendicular to the magnet pole direction. The eddy current density, $\vec{J}$, depends on the conductivity, σ, and the cross product of the velocity, $\vec{v}$, and magnetic field, $\vec{B}$ (see Eq. (1)). The eddy current force is then calculated as the volume integral of the product of the eddy current density and the magnetic field (see Eq. (2)). Mathematically, the two cross products yield a damping force which acts in the direction opposite to the velocity.

$$\vec{J} = \sigma(\vec{v} \times \vec{B}) \tag{1}$$

$$\vec{F} = \int_V (\vec{J} \times \vec{B}) dV \tag{2}$$

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[1] The conductor is a conductive, non-magnetic material. Aluminum and copper are common choices.

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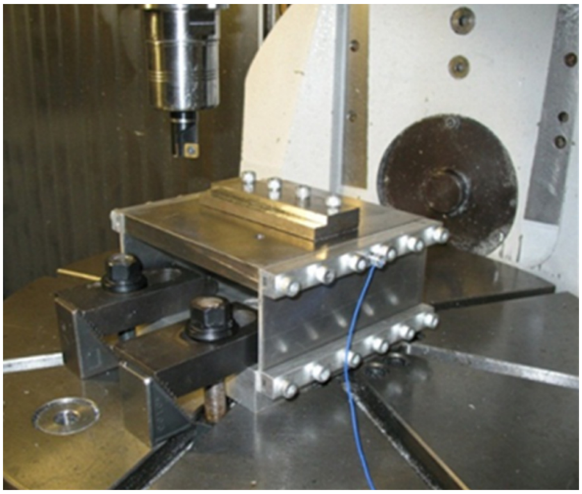

Fig. 1. Example parallelogram, leaf-type flexure used for milling experiments. A workpiece is mounted to the top of the flexure, an accelerometer is used to measure the vibration during cutting, and an inserted cutting tool is pictured.

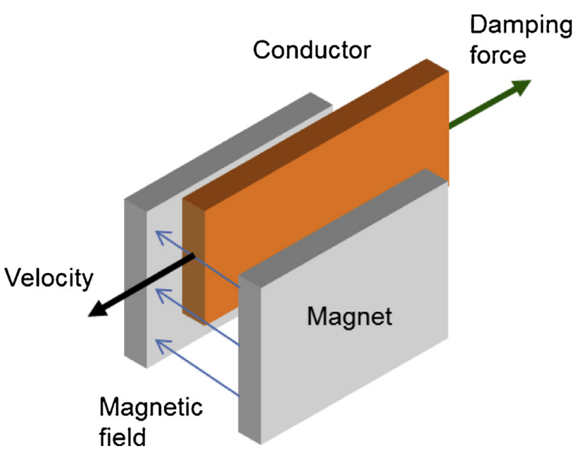

Fig. 2. Schematic of an eddy current damper.

The damping force magnitude, F, is described by Eq. (3), where δ is the conductor thickness, B is the magnetic field strength, S is the magnet surface area, α_1 incorporates surface charge effects, α_2 describes end effects from the finite dimension conductor, and v is the velocity magnitude [10]. The calculations for α_1 and α_2 are provided in Appendix A. As shown, Eq. (3) can be rewritten as the product of a viscous damping coefficient, c, and the velocity magnitude. This viscous damping coefficient enables model-based damping prediction and selection for milling simulation and experiments.

$$F = (\sigma\delta B^2 S(\alpha_1 + \alpha_2))v = cv \tag{3}$$

The eddy current damper concept displayed in Fig. 2 was embedded inside an aluminum flexure as shown in Fig. 3. The conductor was attached to the aluminum flexure platform and two permanent magnet sets were attached to the aluminum flexure base, one on each side of the conductor. The arrangement of the eight 25.4 mm square neodymium magnets (K&J Magnetics BXOXO8DCB) is shown in Fig. 4; aluminum socket head cap screws were used to avoid disrupting the magnetic field.

3. Damped flexure design

The solid model displayed in Fig. 3 was constructed and tested. As shown in Eq. (3), the viscous damping coefficient can

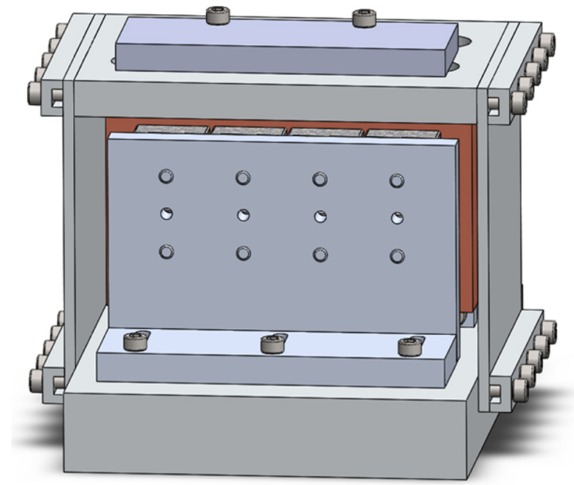

Fig. 3. Flexure with embedded eddy current damper.

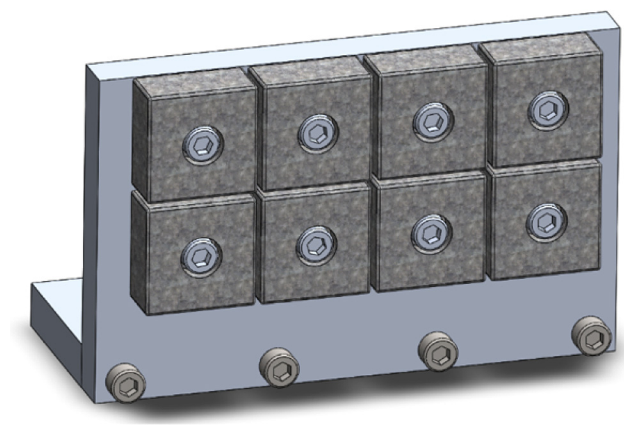

Fig. 4. Permanent magnet mount. The magnets face the conductor with one mount one each side.

Table 1
Eddy current damper design parameters.

Parameter	Value
σ	5.96×10^7 A/V m
δ	19.1 mm
B	4580 Gauss (0.458 T)
S	4.6×10^{-3} m^2
α_1 [a]	0.352
α_2 [a]	−0.177

[a] Calculations for these terms are provided in Appendix A.

be predicted using σ, δ, B, S, and the surface charge/end effect terms, which serve to reduce the damping value (see Table 1). The conductor was a 19.1 mm thick copper plate that extended outside the magnet surface area. The magnetic field strength was measured at 64 locations over the surface of the eight permanent magnets using a gaussmeter (Integrity Design & Research Corp., IDR-329-T). Measurements were performed at a distance of 0.8 mm from the surface; this was the approximate air gap between the magnets and conductor after assembly. The average value for all 64 measurements at the 0.8 mm distance is listed in Table 1.

For the values listed in Table 1, the predicted eddy current damper c value is 192 N s/m. The corresponding dimensionless damping ratio, ζ, is calculated using Eq. (4), where k is the flexure stiffness provided in Eq. (5) and m is the equivalent flexure mass given by Eq. (6) [4]. In Eq. (5), E is the aluminum leaf's elastic modulus (69 GPa), w is the width (101.6 mm), t is the thickness (3.8 mm),