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Reduction of flexible workpiece vibrations with dynamic support realized as tuned mass damper

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Abstract

Elimination of flexible workpiece vibrations with a special damper, attached to workpiece by gluing, is considered. An unconventional approach for tuned mass damper application is proposed, based on damper tuning with respect to a certain spindle rotation frequency chosen for machining. Thanks to such tuning, the damper can operate successfully for workpiece with any frequency response function as long as the proper spindle rotation frequency is kept. Thus, a universal damper can be made using technique described, which can be applied for workpiece of any shape and frequency response with no preproduction preparations, providing an easy and fast way to avoid workpiece vibrations, which would be particularly helpful for small-lot production and model workshops. Theoretical investigations, experimental setup vibration testing and cutting tests were conducted. Workpiece vibrations reduction by 20 times was achieved, while device relative weight was just 2%. Finally, a real flexible part was successfully machined using damper prototype developed.

1. Introduction

Typically aircraft structure parts are substantially flexible which causes undesirable part vibrations during machining [1-4]. To achieve required surface location accuracy and surface finish for a flexible complicated part one may make a special complex fixture. Alternatively, one may carefully adjust spindle rotation frequency to avoid resonance through workpiece frequency response measurement or calculation or just through trial and error. Both of these two techniques require time-consuming preproduction and extra expenditures before the manufacturing may actually begin. For small-lot production and model workshops these leads to significant increase of manufacture time and cost per one part.

A perspective way to avoid tool and workpiece vibrations is using special dampers to increase structure dynamic stiffness. Various types of dampers used in engineering and construction may be divided into three main types: tuned mass dampers, impact dampers, active damping. Tuned mass damper are cheap and effective way of vibrations suppression, but they must be tuned to operate properly [5]. Impact dampers need no tuning and operate in wide frequency range, however, they don’t counteract external excitation but just dissipate energy of oscillations, so, they can’t eliminate vibrations totally [6]. Particle damper is a perspective variant of impact damper for workpiece vibrations reduction in milling [7]. Active damping systems provide effective vibrations suppression and do not require tuning, but they are complicated, expensive and needs external energy supply [8], [9], [10].

A well-known example of successful damper application for metal cutting is Silent Tools, produced by Sandvik Coromant. A long tool is equipped with embedded mass damper, tuned for a certain narrow range of tool extensions, preventing tool chatter during high performance milling. However, there is no

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analogous damper developed for workpiece vibration suppression. The problem is, that use of such damper would require workpiece frequency response function determination (through measurement or calculations) and damper tuning for each new part individually. Thus, one would still need to carry out long-run preproduction procedure for each new part, not better than making complex fixture or spindle speed adjustment.

An unconventional approach for tuned mass damper application can be realised for milling, based on orientation to excitation frequency rather than to workpiece frequency response function [11]. In this paper using of tuned mass damper for workpiece vibrations suppression is considered, and a new approach to mass damper tuning is proposed, which doesn't require workpiece frequency response determination. A universal damper, applicable for workpiece with any frequency response may then be developed, providing an easy-to-use and fast way to prevent flexible workpiece vibrations.

2. Theoretical basis

The basic principle of tuned mass damper (TMD) is that an small additional resonator (weight *m* on spring *k*) is attached to the main construction (weight *M* on spring *K*), Figure 1. Damper parameters *m* and *k* should be tuned to provide certain damper performance. Let sinusoidal external force *F* with amplitude F_0 and frequency *f* acts on main construction. Elementary analysis shows that if the damper inherent frequency is equal to frequency of external excitation *f*, than the damper would vibrate in opposition with excitation and counteract it. As a result, the damper would compensate external force, making resultant force, acting on main construction, zero, and eliminate main construction vibrations completely. The external force, acting on main construction, will in that case result just in vibrations of the damper but not the main construction.

In practice tuned mass damper is usually realized with sufficient internal friction and inherent frequency close to main construction resonance in order to avoid intensive forced vibrations for random excitation and self-excited vibrations. Such technique is too complicated to apply for workpiece vibrations suppression, as it implies workpiece frequency response determination and damper tuning for each new part to be manufactured. However, for milling the frequency of excitation is fixed and determined in advance, as it is ruled by spindle rotation frequency and number of teeth on cutting tool. This particularity of the problem under consideration enables to implement an unconventional approach of TMD application for workpiece vibration suppression in milling. One can use TMD with low internal friction, tuned so that its inherent frequency coincides with tooth passing frequency for certain spindle speed chosen to be used during machining. In this case, a small damper can almost totally eliminate workpiece forced vibrations with no regard to workpiece frequency response. Such universal damper can be attached to workpiece of any shape and would prevent vibrations of workpiece with any frequency response, providing fast and easy way to avoid workpiece vibrations.

Frequency response function for system shown on Figure 1 can be easily calculated [11] to evaluate damper effectiveness, Figure 2. The damper creates a trough in the frequency response with practically no response at damper inherent frequency (630 Hz). If the damper is tuned so that its inherent frequency coincide with coming tooth passing frequency, workpiece forced vibrations would be very small during machining.

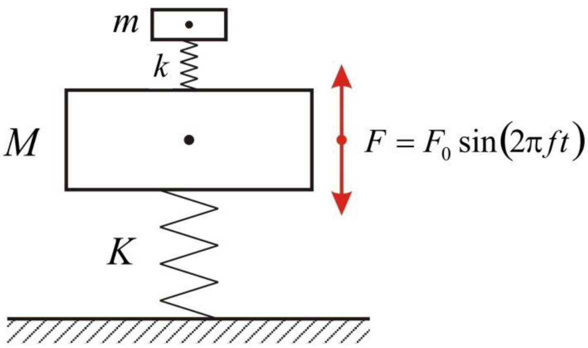

Figure 1: Tuned mass damper diagram.

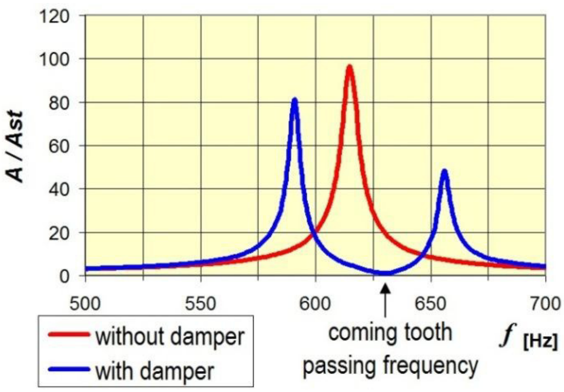

Figure 2: Calculated frequency response function for workpiece with and without tuned mass damper. *f* – excitation frequency, A/A_{st} – ratio of workpiece dynamic response to static deflection.

To investigate effectiveness of vibration suppression along the whole workpiece with damper in one point, workpiece dynamics simulation was conducted using FEM. A steel plate 160 x 20 x 3 clamped on both ends was considered as a workpiece. A sinusoidal force excitation with frequency 500 Hz, which is close to workpiece resonance frequency, was applied to various points on the workpiece one by one and resultant vibration amplitude was calculated. The damper was realized as a transversal plate with free ends, and its sizes 110 x 10 x 2 were adjusted so that its natural frequency was equal to excitation frequency. Three cases were considered: workpiece without damper, workpiece with damper in the middle point and workpiece with an additional rigid support instead of damper. The result are shown on Figure 3. The damper successfully suppresses vibrations over whole workpiece. Moreover, the damper is practically as effective as an additional rigid support. So, the damper works like dynamic support, and such support can be rapidly mounted on workpiece of any shape wherever addition fixation required with no need in manufacturing of special fixture.

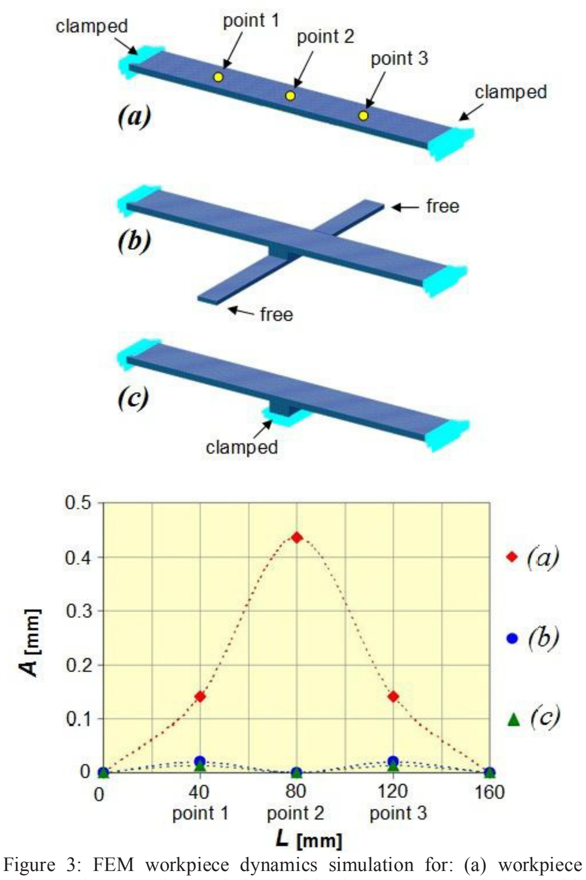

Figure 3: FEM workpiece dynamics simulation for: (a) workpiece without damper; (b) workpiece with damper; (c) workpiece with additional support. *L* – distance from clamps; *A* – vibrations amplitude.

3. Setup vibration testing

A setup consisted of a test part (thin steel compressor blade) clamped in fixture, damper prototype, small vibration exciter and accelerometer was constructed to experimentally observe vibration suppression by damper. The test part and the damper prototype are shown on Figure 4. In this test damper prototype was just a small steel beam with two symmetrical weights on its ends mounted on stand with knob for gluing to workpiece. The weights can be rearranged along the beam to adjusted inherent frequency of the damper so that it would equal to tooth passing frequency for some certain spindle speed. Sine signal of continuously changing frequency was send to exciter to measure workpiece frequency response with and without damper. The obtained results, shown on Figure 5, closely correlate with theoretical predictions on Figure 2. There is practically no workpiece response at damper inherent frequency.

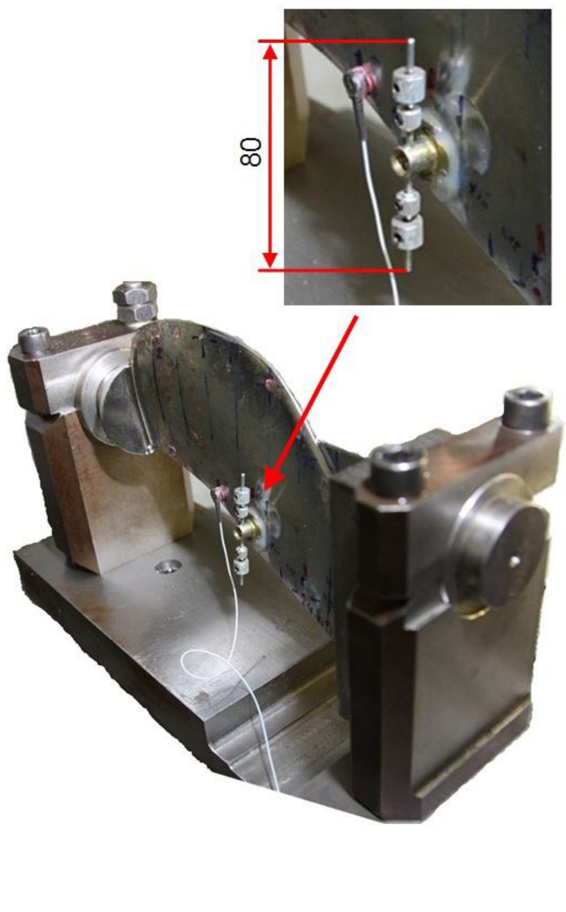

Figure 4: Part and damper for setup vibration testing and cutting test.

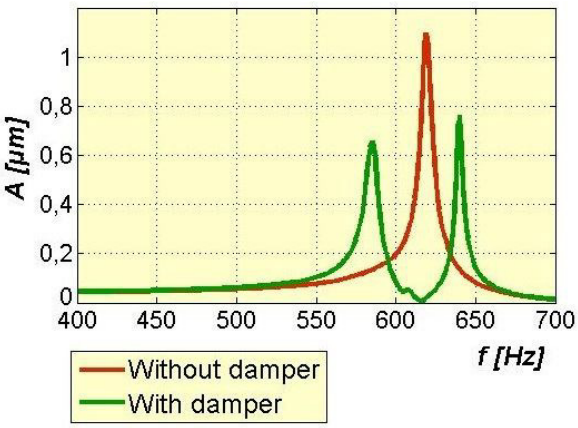

Figure 5: Transformation of workpiece frequency response function by damper. *f* – excitation frequency, *A* – workpiece response.

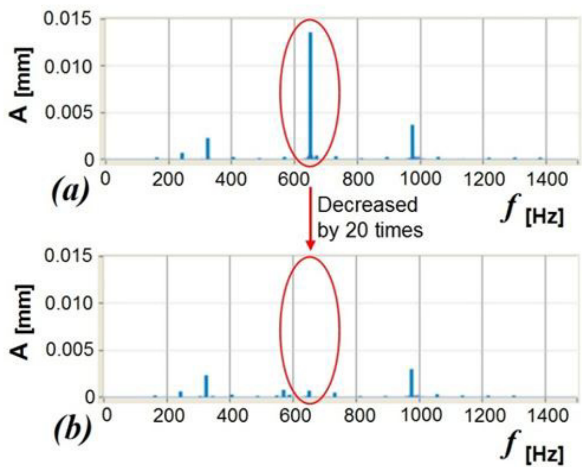

Figure 6: Workpiece vibrations spectrum during cutting test without damper (a) and with damper (b). Damper inherent frequency was 650 Hz.

4. Cutting test

Theoretical analysis, FEM simulations and setup vibration testing don't reflect feedback effect between workpiece vibrations and cutting force, and, so, don't allow to simulate milling process entirely. Sophisticated phenomena such as self-exited oscillations may occur in real machining. Cutting test was conducted to check damper performance. The same workpiece used previously for setup testing was machined. Several accelerometers were used to measure workpiece oscillations during machining. Spindle speed was consciously chosen for excitation frequency to be near the workpiece resonance. When intensive vibrations, occurred near midpoint of blade span, causing clearly heard blade signing, machining was stopped and a damper (same as in setup testing) was attached to the workpiece on the underside by glueing. The weight of the damper was just about 2% of blade weight. Spindle speed was 4875 rpm, the cutting tool had 4 teeth, so, tooth passing frequency was 325 Hz. Workpiece resonance frequency was around 650 Hz, and intensive vibrations were induced by second harmonic of excitation (at doubled tooth passing frequency). So, positions of damper weights along the beam were adjusted in advance so that inherent frequency of the damper was equal to 650 Hz. After the damper was attached, machining was continued. With damper the sound of workpiece singing disappeared, and accelerometers showed that workpiece forced vibrations amplitude was decreased by 20 times, Figure 6.

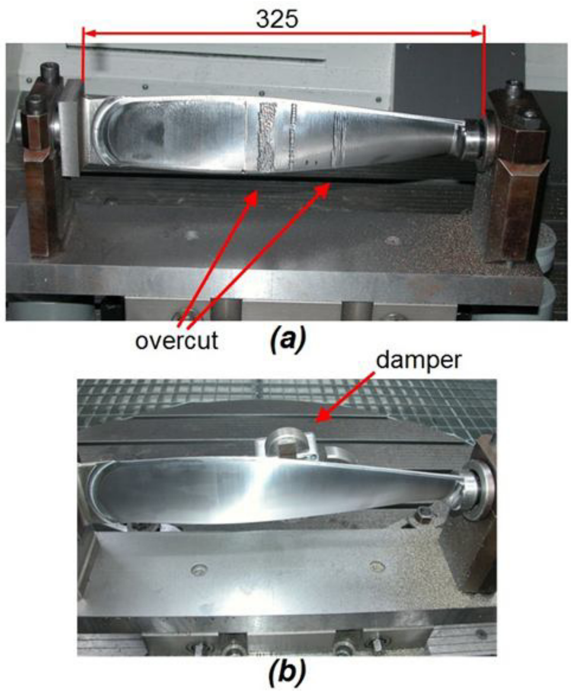

Figure 7: Flexible part machined without damper (a) and with damper (b).

5. Real Part manufacturing

A very flexible workpiece (scaled-down model of helicopter vane for wind tunnel testing) was manufactured with and without damper prototype developed (Figure 7). A larger damper was made to broaden damper tuning tolerance. Severe workpiece vibrations with amplitude more than 1 mm occurred without damper. The noise of vibrations was very loud, surface finish was very bad and the workpiece was spoilt because of heavy overcut. Moreover, cutting tool was finally broken. The same workpiece Identical workpiece was then machined with damper attached on the underside. With damper just small vibrations occurred, the noise was much more quiet, the surface finish was good (which one may clearly see on the given picture) and, according to control measurements, the dimensional accuracy met the required tolerance.

6. Conclusion

The developed damper provides fast and easy way to avoid flexible workpiece vibrations in milling. No workpiece frequency response measurement or calculation needed to apply the damper, it's universal. One restriction is that the spindle rotation frequency to be used during machining should correspond to those damper was tuned to. A set of dampers with fixed tuning to usual spindle speeds can be used as equipment for workpiece vibration avoidance. Alternatively, an easy-retunable damper can be made, so that one needs just to rearrange and fix a weight along he beam with scale of spindle speed values. A complex damper embodying assembly of tuned mass dampers can be used to compensate several harmonics of cutting force at once.

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