CIRP Annals - Manufacturing Technology 62 (2013) 415–418

Contents lists available at SciVerse ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

A solution for minimising vibrations in milling of thin walled casings by applying dampers to workpiece surface

Kiran Kolluru, Dragos Axinte (1)*, Adib Becker

Rolls-Royce University Technology Centre (UTC) in Manufacturing, Faculty of Engineering, University of Nottingham, UK

ARTICLE INFO

Keywords:
Damping
Milling
Finite element method (FEM)

ABSTRACT

Milling of large thin walled casings with complex features needs appropriate damping solutions to achieve required workpiece surface quality when utilising aggressive machining parameters. In this paper a novel surface damping solution composed of a thin flexible layer mounted with distributed discrete masses attached with viscoelastic layer is presented. Damping of higher frequencies through a flexible layer and subsequent lower frequencies through added masses enables damping over a wide bandwidth. Finite element modelling and validation of the proposed solution showed a significant damping of workpiece and corresponding reduction in machining vibration by more than four times.

1. Introduction

Machining of thin wall structures is a challenging task mainly due to the vibrations that arise during the process which affect part dimensional accuracy and its surface finish. A trend towards adopting light weight structures in all the sectors, viz. aerospace, automotive seems to intensify this problem.

Chatter in metal cutting was researched for various machining operations [1,2] while methods for their avoidance have been proposed including both selection of stable cutting parameters [3] and fixturing solutions [4]. While the former solution seems to have been reported more for simple geometries (e.g. straight thin walls) where measuring dynamic response is straightforward and relatively simple (in terms of variation of dynamic response across structure), fixturing approach could be considered attractive in a wide range of industrial cases to provide a stable workpiece for machining. While the stability lobes are very useful in determining chatter-free spindle speeds and depths of cut, their application becomes difficult when machining thin-walled complex component assemblies (e.g. milling of welded casings). Recently, a strategy for thin part machining using sacrificial structure preforms [5] was proposed; while this is useful for improving the stiffness of individual thin-walled parts, incorporating preforms in ring-type components (e.g. aerospace casings) to be welded may not be a viable solution.

In reference to fixturing approaches, to enable the avoidance of dynamic instability, both passive and active damping solutions have been studied; the former includes rubber diaphragms [6], tuned viscoelastic dampers [7], and low-melt alloys [4,8] while the latter make use of piezoelectric damping [9] or magneto-rheological fluid [10]. Passive damping solutions became popular in industry due to their easy adaptability and simplicity in usage in a wide range of applications; on the other hand, active damping solutions, in spite of their ability to cover wide bandwidths, are not favoured due to the complexity when implementing them in real industrial environments. Nevertheless, the passive damping methods are not infallible; for example, the application of rubber pressurised diaphragms [5], apart from limiting the access to internal features, they cannot be mounted on complex thin-walled assemblies that display other internal parts of irregular geometries (e.g. vanes, plumbing lines passing internally) thus, making such methods inadequate for addressing machining vibration in many industry scenarios.

This paper presents a set of theoretical and validation studies of a novel damping solution that can be applied to large thin-walls of assemblies of various geometries. It consists of a thin conformable layer, carrying a set of discrete masses, attached to the structure with an adhesive material (e.g. viscoelastic tape). The research describes the construction and working principle of the solution, the effect of surface damper in impact excitation, its verification by finite element (FE) modelling and experimental validations to evaluate the effectiveness in damping milling vibrations of thin-wall structures; the proposed solution, being compact, can be used locally or on the whole structure, to any internal/external part of the assemblies, while its conforming nature allows its application to various part geometries.

2. Surface damping solutions: approach for thin-wall milling

Although damping solutions have been reported to reduce automotive panel vibrations/noise levels, minimisation of machining vibrations of thin-walled structures necessitates development and evaluation of alternative/dedicated surface damping solutions for the following reasons:

- The frequencies to be damped while machining a thin-wall casing need not be always one of its resonant modes. As studied [11], the dominant frequencies on a thin-walled parts during milling could depend on the stock of removed material (e.g. radial depth a_e in peripheral milling): (i) for smaller a_e values tool natural frequency dominate during contact of cutting tooth

* Corresponding author.

0007-8506 © 2013 CIRP. Open access under CC BY license.
http://dx.doi.org/10.1016/j.cirp.2013.03.136

while workpiece fundamental modes dominate during non-contact period; (ii) for higher a_e values the tool natural frequency is dominant. So, in milling thin-walled parts, not only the workpiece resonant vibrations but also imposed tool's resonant vibration needs to be minimised. Hence, the proposed solution should offer not only damping but also improve the mass and the stiffness of the structure.

- The frequency range to be damped in machining can be typically up to 10 kHz and depends on the stiffness of connection dynamics [12] and hence the proposed damping system should be effective over wider bandwidth.
- While for the automotive applications, due to light-weight requirements, the treatments are designed for maximum energy dissipation only through shear deformation of viscoelastic layer, for fixturing applications in machining, mass addition is not as critical and hence, in addition to damping, mass and stiffness improvement need to be considered.

Considering above factors, a novel surface damping solution is proposed, modelled and validated on a thin-walled casing (Fig. 1) that replicates some features of a real aerospace component.

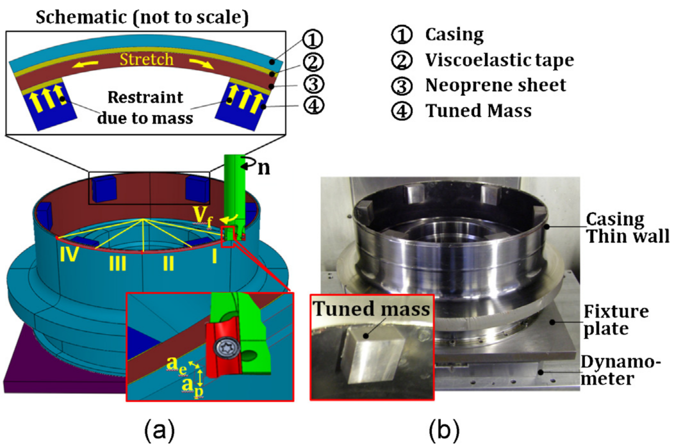

Fig. 1. Concept of surface damping solution (a) and test casing (b).

The proposed damping solution consists of a flexible viscoelastic substrate layer (e.g. neoprene) on to which discrete masses are attached at particular locations determined by analysis of the results from both impact testing and FE modelling. The substrate layer, whose role is to conform to any part geometry and offer damping, can be mounted on thin-walled casing with a viscoelastic or suitable adhesive tape. The attached masses not only help in adding mass to the workpiece (hence increasing inertial forces) but also in anchoring the substrate at intermediate points allowing it to stretch (see insert Fig. 1a) during vibration and hence imparting stiffness to the workpiece.

Thus, this solution improves upon all three characteristics (mass, stiffness and damping) of fixturing system while being compact making it useful where elaborate conventional fixturing cannot be used due to part features as explained before.

In the following, the effectiveness of the proposed damper solution is evaluated through impact excitation tests and supported by appropriate FE modelling. To address the industrial machining conditions (e.g. generation of pockets/bosses on the thin wall), peripheral milling (on various sectors, I–IV – Fig. 1, of the external casing diameter) was carried to demonstrate the effectiveness of the proposed novel approach.

3. Effect of the proposed surface damper in impact excitation

It has been documented [11] that at low depths of cut in milling of thin-walled casings the workpiece modes are dynamically dominant. As this paper deals with this case (finish milling), damping solution for the workpiece is evaluated by FE modelling and validated through impact hammer testing. The thin-walled casing (Fig. 1) utilised for this study is made of Waspaloy® and has the following dimensions: 2.5 mm wall thickness, 95 mm height and 365 mm outer diameter. It has a significant mass at the bottom hub (82 kg) on which only the thin wall of the casing (4 kg) is modally active; hence, in this study only the thin wall portion was considered for dynamic response measurement.

The impact testing was performed in three configurations: *Undamped*; *Viscoelastic surface-based damping* with only a flexible elastic sheet (marked ② and ③ – Fig. 1a); *Mass stiffness enhanced damping* where on the flexible sheet a set of masses, tuned for the dominant modes after mounting the sheet (marked ②, ③ and ④ – Fig. 1a) were attached. The results (blue curves – Fig. 2) of impact hammer testing on these configurations are summarised below:

- *Configuration 1 – Undamped*: From Fig. 2a it can be noted that the undamped casing has many closely spaced modes extending up to higher frequencies (15 kHz).
- *Configuration 2 – Viscoelastic surface-based damping*: Mounting 3 mm thick neoprene sheet with a viscoelastic tape on the casing has a significant effect in damping the high frequency modes (Fig. 2b); *about two orders reduction in acceleration can be noticed*. This damping is more likely to be a contribution from the neoprene sheet and to some extent due to viscoelastic tape. However, in this case, the low frequency modes that are in general more likely to get excited during machining were not fully damped.
- *Configuration 3 – Mass stiffness enhanced damping*: In this work, the added masses were tuned for the first fundamental mode of workpiece (after mounting neoprene), 1260 Hz, as shown in Fig. 2b and also seen to be dominant in acceleration signal, Fig. 3, acquired during milling (as later discussed). While the number of masses (six – one each at six antinodes of mode shape) to be mounted was decided based on mode shape of dominant mode (Fig. 3), the weight of each mass was configured considering two aspects: necessity to damp modes over wide frequency range and providing sufficient mass so as to act as an anchor for flexible sheet at mounting points and hence to enable stretching of the flexible sheet. With these considerations, six masses, each 0.2 kg (5% of vibrating mass, 4 kg), were attached to the thin wall (Fig. 1).

The dynamic response of the casing in Configuration 3, neoprene sheet and masses – Fig. 2c – shows damping of all neighbouring modes in addition to the targeted mode due to the high mass ratio of dampers; moreover, the fundamental frequency shifted due to mass addition. However, the relative reduction in amplitude of the response is not significant as compared to

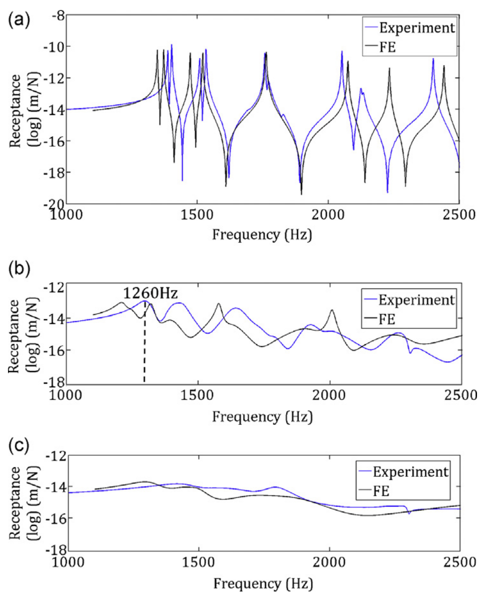

Fig. 2. Impact hammer testing results on thin-walled casing in comparison with FE predictions in the following conditions: (a) undamped; (b) with neoprene sheet; (c) with neoprene sheet and tuned masses.

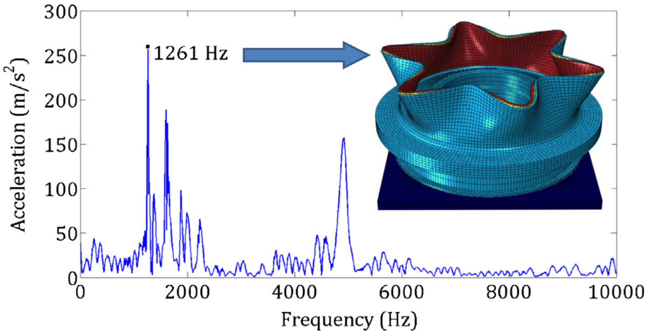

Fig. 3. FFT of machining signal of casing with neoprene showing the dominant mode and shape to enable selection of damping solution.

neoprene sheet alone (Configuration 2) – only an order of magnitude. This can be explained as the vibration generated by a single impact damps out quickly due to structural damping of casing and neoprene; hence, the effect of stiffness due to stretching of neoprene is not significant for single impact excitation.

FE analysis using Abaqus® was carried out to study the dynamic behaviour of the casing for all the three configurations. From the preliminary modal test data a structural damping of 0.1% was used for undamped casing.

For FE modelling of damping effect, the viscoelastic properties (storage and loss modulus vs. frequency) of the viscoelastic tape 3M® ISD112 were taken from the manufacturer's data sheet while that of neoprene rubber sheet were evaluated using dynamic mechanical analysis (DMA). DMA was performed in-house using Dynamic Mechanical Analyser (TA Instruments DMA Q800) on a neoprene specimen (25 mm × 8 mm × 3 mm) in tensile mode simulating actual operating condition of stretching; with this, the specimen is subjected to sweeping frequencies from 0.1 to 200 Hz at isothermal temperatures varying from −40 °C to +60 °C in stages. This data was then extended up to 10 kHz through frequency shifting using time–temperature superposition principle.

The variation of storage and loss modulus within the frequency range 0–10 kHz, Fig. 4, shows that the neoprene sheet used in the experiment is in rubbery state in this frequency range and the glass transition point is well beyond this range.

The increasing loss modulus with frequency explains the damping of higher frequency modes of the casing as can be noticed in Fig. 2c. Harmonic analysis was carried out on the FE model using direct integration to take into account the frequency dependent variation of viscoelastic properties. Hence, the dynamic response of casing as predicted by FE (black curves – Fig. 2) is overlaid on the experimental results obtained by impact hammer testing. The maximum error in frequencies observed was, respectively, 4%, 7% and 8.5% for undamped, with flexible layer, and flexible layer with masses. This could be minimised through updating FE model – boundary conditions and material properties. However, for the present study this level of error was considered acceptable and shows the effectiveness of surface damping solution in damping the workpiece frequencies typical in milling of casings. In the next section, the effect of proposed solution will be presented in actual milling operations.

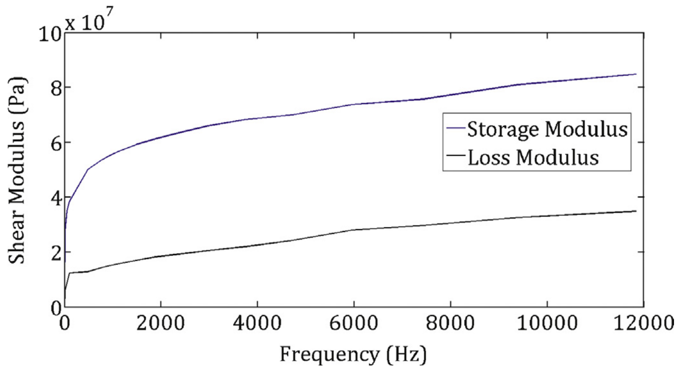

Fig. 4. In-house evaluation of shear modulus vs frequency of neoprene.

4. Effect of surface damper on milling thin-walled casing

The validation of the proposed damping solution in near-industrial condition was conducted by peripheral milling of the test thin-walled casing. In addition, the frequency content of the acceleration signals acquired during milling were analysed by Fourier transformation to identify the dominant modes contributing to vibration. Milling parameters were chosen to reflect industrial conditions over a range of values (a_p = 0.5–2 mm; a_e = 0.5–2 mm) with constant cutting speed (v_c = 40 m/min) and feed per tooth (f_z = 0.1 mm/tooth). To analyse the frequency content of the signal for one tool revolution, acceleration and cutting force during machining were synchronously measured in one quadrant of casing in four sectors (see I–IV, Fig. 1). This break-up into four sectors was needed as significant amount of data was collected at higher sampling rate (10^6/s) to obtain better frequency resolution of spectrum. The reduction in machining acceleration is quantified in terms of the root mean square (RMS) value of the signal acquired which is exemplified (Fig. 5) when machining quadrant II of the casing for the three configurations.

As can be seen from Fig. 5a the reduction in vibration on casing with viscoelastic surface-based damping (Configuration 2) alone is not significant enough (only 1.63 times) with respect to the undamped structure (Configuration 1). This could be due to the fact that, unlike in single impact excitation (as explained in Section 3), the cutting energy is continuously fed into the casing through forced vibration during cutting action of the tool.

However, when the masses are attached (Configuration 3) the vibration of the thin-wall casing during milling reduced by about 4.2 times. As explained earlier, this is mainly due to the added mass effect combined with increased stiffness offered by stretching neoprene layer between two masses in addition to the damping caused by compressing the neoprene layer itself. The stretching of neoprene sheet between two masses can be noticed from the elastic strain energy, simulated by FEM, developed in the sheet with and without masses (Fig. 6).

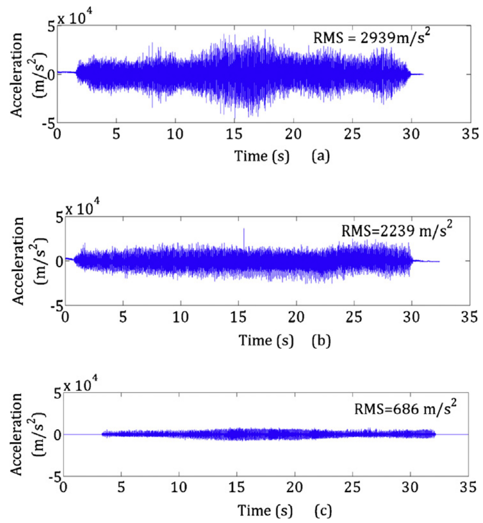

Fig. 5. Examples of vibration signals when milling of thin-walled casing: (a) undamped; (b) with neoprene sheet; (c) with neoprene and 6 tuned masses (a_p = 2 mm, a_e = 0.5 mm).

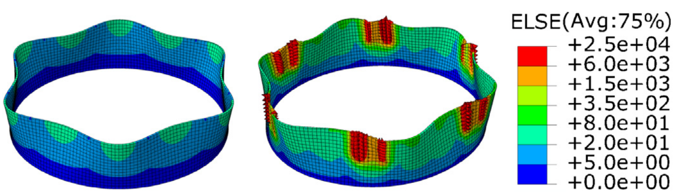

Fig. 6. Elastic strain energy (ELSE) map of neoprene sheet for first mode shape without (left) and with masses mounted on casing (right).

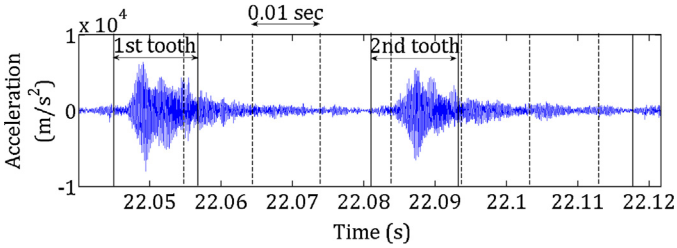

Fig. 7. Sections across which FFTs are taken for acceleration signal.

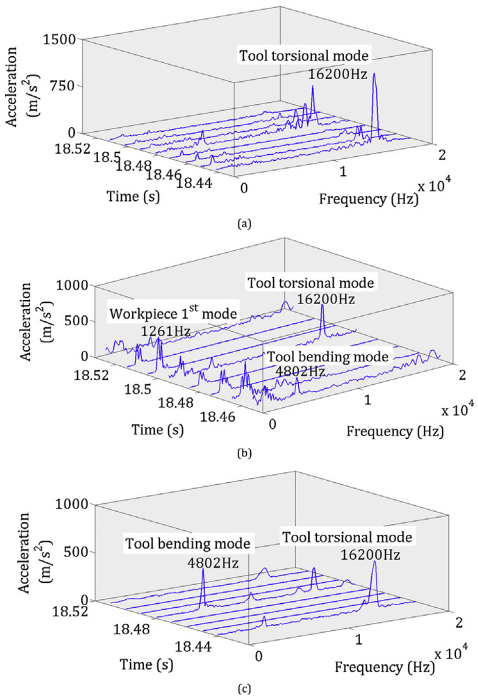

Fig. 8. Frequency spectra for one rotation of tool: (a) undamped; (b) neoprene sheet; (c) neoprene sheet with 6 tuned masses.

The frequency content in the machining vibration signal was studied by performing fast Fourier transformation (FFT) across equi-spaced sections, Fig. 7, for one revolution of tool. This kind of time–frequency analysis gives a better picture of evolution of frequencies when machining is progressing, i.e. when the tooth engages and leaves the cut.

The frequency spectra shown in Fig. 8a clearly depict the dominant presence of tool torsional mode (16,200 Hz, as observed from FE modal analysis of tool) along with the workpiece modes. This tool dominance is due to forced vibration imparted by the tool to the thin-walled casing; more on this coupled dynamic response is reported in [11]. Attaching the neoprene sheet to the casing, Configuration 2, proved to damp most of the high frequency workpiece modes (Fig. 8b) leaving some of the low frequency workpiece mode (1260 Hz, as also shown in Fig. 2b) and tool modes undamped, due to its dynamic behaviour wherein loss factor increases with frequency as presented in Fig. 4. Mounting the six tuned masses, Configuration 3, not only damped all the workpiece modes (Fig. 8c), but also reduced the amplitude of induced tool's imposed modes, possibly due to high mass ratio of the tuned masses. Also the rigidity imparted to thin wall due to added mass and stiffness makes coupling of tool's bending mode (4802 Hz) with workpiece significant. This explains the significance of mass and stiffness improvement for a thin wall to minimise vibrations in non-resonant situations (with forced tool frequency) where damping (such as due to viscoelastic and neoprene) alone is not sufficient.

5. Conclusion

This paper presents a novel surface damping solution that can be applied to thin-walled complex welded casings to minimise milling vibrations. The main advantages of proposed solution are: (i) ability to be applied onto complex assemblies (e.g. obstructing parts/features such as plumbing lines); (ii) able to be mounted on the whole structure or on a locally vibrating panel; (iii) conformable to complex geometries; (iv) quick application on the workpiece with no mechanical damage/chemical contaminations.

The proposed damping solution was studied for its effectiveness in dynamic impact testing and milling trials. While the former is useful in determining the effectiveness on damping workpiece resonances, the latter evaluates it in the presence of coupled workpiece–tool vibrations.

It was noticed that the flexible (neoprene) sheet alone dampens only the high frequency content in the vibration signal due to its dynamic properties (loss factor) leaving the low frequencies undamped. Mounting the masses on the flexible sheet helps not only in improving the mass of structure but also the stiffness of casing through the stretching of flexible sheet. In the dynamic impact testing trials, the peak response of the undamped casing was reduced by two orders by mounting the neoprene sheet and an incremental reduction by one order with masses. The reduction in relative effectiveness with the masses could be due to already sufficient damping of single impact excitation by structural damping of neoprene itself.

In actual machining trials, however, the proposed damping solution showed significant reduction in vibration (about 4.2 times) as compared to mounting flexible sheet alone (about 1.3 times). This can be explained due to the coupled interaction of tool with workpiece where the tool's resonant frequencies significantly dominate the vibration spectrum; the added mass and stiffness offered by stretching flexible substrate contributed more. Hence the proposed solution signifies the importance of improving the mass and stiffness of thin walled structures in the presence of forced tool's vibration. This work finds it relevance for high value industries (i.e. aeroengines) where thin-walled casings need to be machined at high surface quality standards.

Acknowledgements

The authors would like to thank EPSRC and Rolls-Royce for providing the funding under Dorothy Hodgkin Postgraduate Award scholarship for this research. They would like to thank Mr. P. Winton of Rolls-Royce and Dr. M. Raffles of Rolls-Royce UTC for their support through discussions.

References

[1] Altintas Y, Weck M (2004) Chatter Stability of Metal Cutting and Grinding. *Annals of CIRP* 53(2):619–642.
[2] Guillem Q, Joaquim C (2011) Chatter in Machining Process: A Review. *International Journal of Machine Tools and Manufacture* 51:363–376.
[3] Budak E, Altintas Y (1998) Analytical Prediction of Chatter Stability Conditions for Multi-Degree of Systems in Milling. *Transactions of the ASME Journal of Dynamic Systems Measurement and Control* 120:22–30.
[4] Aoyama T, Kakinuma Y (2005) Development of Fixure Devices for Thin and Compliant Workpieces. *Annals of CIRP* 54(1):325–328.
[5] Smith S, Wilhelm R, Dutterer B, Cherukuri H (2012) Sacrifical Structure Preforms for Thin Part Machining. *Annals of CIRP* 61:379–382.
[6] Geng, Z., 2008, Adaptive Design of Fixture for Thin-walled Shell/Cylindrical Components, International Patent WO 2008/107672 A1.
[7] Rashid A, Nicolescu CM (2008) Design of Tuned Viscoelastic Dampers for Vibration Control in Milling. *International Journal of Machine Tools and Manufacture* 48:1036–1053.
[8] Choi DS, Lee SH (2001) A New Rapid Prototyping System using Automated Fixturing with Feature Based CAD/CAM. *Journal of Materials Processing Technology* 113(1):285–290.
[9] Sims N, Bayly P, Young K (2005) Piezoelectric Sensors and actuators for Milling Tool Stability Lobes. *Journal of Sound and Vibration* 281:743–762.
[10] Sathianarayanan D, Karunamoorthy J (2008) Chatter Suppresion Boring Operation using MR Fluid Damper. *Materials and Manufacturing Processes* 23(4):329–335.
[11] Kolluru, K., Axinte, D., (2013), Coupled interaction of dynamic responses of tool and workpiece in thin wall milling, Journal of Material Processing Technology, In Press, http://dx.doi.org/10.1016/j.jmatprotec.2013.03.018
[12] Budak E, Ertürk A, Özgüven HN (2006) Modeling Approach for Analysis and Improvement of Spindle-Holder-Tool Dynamics. *Annals of CIRP* 55(1):369–372.