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Identification of transfer function by inverse analysis of self-excited chatter vibration in milling operations

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ABSTRACT

Analysis of the stability limits in self-excited chatter vibration requires the transfer function of the mechanical structure, and thus the accuracy of the analytical prediction strongly depends upon the accuracy of the transfer function, which is generally measured by the impulse response method. However, it is often difficult to measure the transfer function accurately, especially in a case where a small-diameter tool or a workpiece is flexible, or when the transfer function changes as a result of spindle rotation. This paper presents a novel method of identifying the transfer function by utilizing inverse analysis of the self-excited chatter vibration measured during an end milling experiment. In the proposed method, the transfer function can be identified to minimize errors between chatter analysis and experimental results. A basic end milling test verified that the transfer function identified by the developed method is similar to that measured by the impulse response method, and that it yields a more accurate prediction of the stability limits. Further applications using a small-diameter end mill were conducted, and the feasibility of identifying the transfer function by using the proposed method was investigated.

1. Introduction

Self-excited chatter vibration imposes a limit on machining productivity and can result in a significant reduction in tool life in the end milling process. The prediction of chatter stability, which can lead to more efficient and more stable machining conditions, is a major focus of research in machining technology. As a means of predicting stability limits, analytical models of the end milling process with self-excited chatter vibration have been developed in a number of previous studies [1,2]. These analyses have all required the transfer function—or the frequency response function (FRF)—of the mechanical structure in order to predict chatter stability. The accuracy of an analytical prediction strongly depends upon the accuracy of the transfer function obtained for the most flexible mechanical structure, which is generally measured by the impulse response method and then represented by identified modal parameters [3]. If there is a large error in the measurement of the transfer function, errors in prediction under chatter-free conditions, such as spindle speed and depth of cut, will no longer be negligible. Therefore, accurate measurement of the transfer function is important, as well as modeling of the process with chatter vibration. However, it is often difficult to measure the transfer function accurately by means of experimental identification through hammering tests. For example, if an accelerometer is affixed to a small structure, such as a small-diameter end mill or a very small workpiece, the mass of the accelerometer itself is not negligible and causes large errors in the measurement [4]. In addition, it is often difficult to excite structures and to measure vibration at an intended position along an appropriate direction due to complicated geometry. The measured frequency range is also limited, as it is dependant on the frequency ranges produced by a hammer and properly recorded by a sensor. In order to predict the FRF of a mechanical structure accurately, the use of a receptance coupling technique has been proposed in past research [5]. As finite element analysis-based predictions of FRFs and experimental modal analyses can be combined, this method is useful even when predicting FRFs of mechanical structures with miniature structures. However, finite element analysis requires unknown parameters in damping, which are generally difficult to estimate. In addition, if the setup includes the rotating spindle structure and it is the very flexible component in the setup, its transfer function may change considerably due to the rotation of the spindle [6,7]. In such a case, it is extremely difficult to identify the FRFs of a rotating structure accurately.

This paper presents a novel method to identify the transfer function in the end milling process. Chatter stability is generally predicted by modeling the cutting process and by using measured FRFs. This paper focuses on the use of chatter vibration measured

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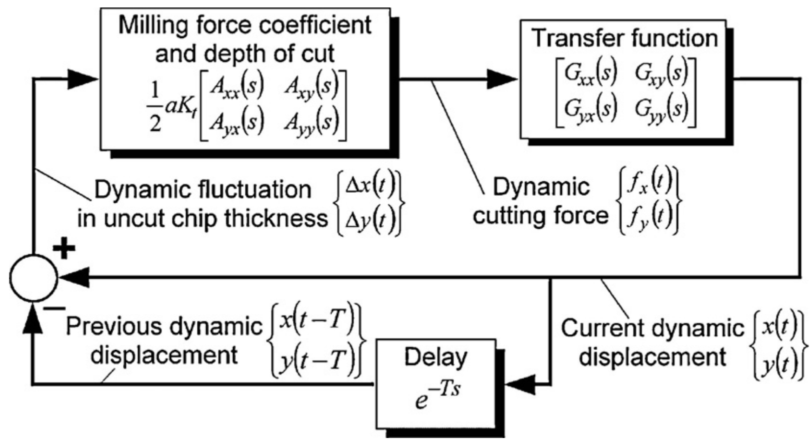

Fig. 1. Block diagram of end milling process.

during cutting. The transfer function is identified inversely in the proposed method by analyzing the chatter vibration measured during the end milling process. As the proposed method does not require a hammering test, the transfer function can be identified accurately—regardless of the conventional issues mentioned above.

Henceforth, relational expressions are formulated to attain an inverse analysis of self-excited chatter vibration. For simplification, the experimental and the analytical procedures for the identification of the transfer function are organized for the isotropic system. End milling experiments with a flexible spindle-tool system are carried out to verify the proposed method, and subsequently the transfer function is identified and compared with the transfer function measured by the impulse response method.

2. Identification of transfer function by inverse analysis of chatter vibration

2.1. Outline of proposed identification method of transfer function

The chatter stability limit in cutting depends upon the transfer function of the mechanical structure and the cutting process. Fig. 1 is a block diagram showing the end milling process. The cutting process and the transfer function form a closed-loop system. By modeling the theoretical relations between the two, chatter stability can be predicted analytically. The stability limit in the axial depth of cut and the chatter frequency in end milling can be estimated from the transfer function of the mechanical structure and other conditions, such as tooth passing period, radial depth of cut, and specific cutting force.

The aim of this paper, however, is to provide a method of identifying the transfer function of a mechanical structure by inverse analysis of chatter vibration. The theoretical relations in the end milling process can also associate the transfer function with the experimentally measured chatter frequencies and the stability limits in the axial depth of cut. Therefore, the transfer function can be identified by inverse analysis of self-excited chatter vibration when the stability limits are given by the experiments. This paper focuses on the identification of the transfer function in the end milling process. Note that this idea is also applicable to other cutting operations, such as turning, boring, and ball end milling. In addition, it can be also extended to identify different parameters, such as specific cutting constant, and process damping parameters [8,9].

In the proposed method, the transfer function is identified by analyzing the relations among chatter frequency, tooth passing period, stability limit of the axial depth of cut and other cutting-process parameters. In order to attain reliable identification efficiently, the cutting tests need to be carried out under

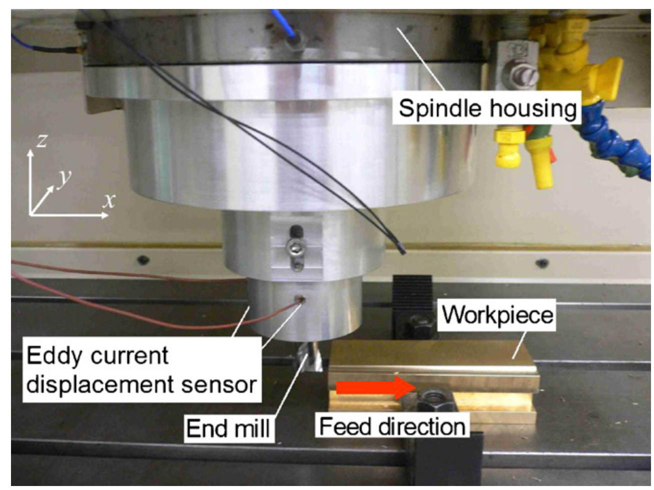

Fig. 2. Experimental setup.

appropriate conditions and the stability limits of the axial depth of cut and the chatter frequencies need to be measured accurately. The proposed identification procedures are followed as described below:

(1) End milling experiments are carried out at several spindle speeds, and the parameters in stability limits, i.e., critical depth of cut a_{lim}, chatter frequency f_c and phase shift ε, are examined.
(2) Modal parameters are identified as analytical results that agree with experimental results.
    (2.1) Initial values of modal parameters are identified.
    (2.2) Modal parameters are optimized by means of Algorithms 1 or 2, which are described in detail below.

2.2. Experimental procedure

In the proposed method, stability limits in the axial depth of cut and the chatter frequencies need to be measured at several spindle speeds. Fig. 2 shows the experimental setup employed to verify the proposed method. The workpiece (a block of brass) is fixed to the rigid table of a general machining center (MX45VAE, Okuma). The top surface of the workpiece is slightly inclined to the horizontal plane. A high-speed steel (HSS) end mill with two flutes is fed along the horizontal direction, and thus the axial depth of cut is increased gradually during machining. Chatter vibration is detected by measuring the radial displacement of the tool shank by means of two eddy current displacement sensors fixed to the spindle housing.