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Matching synchrosqueezing transform: A useful tool for characterizing signals with fast varying instantaneous frequency and application to machine fault diagnosis

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ABSTRACT

Synchrosqueezing transform (SST) can effectively improve the readability of the time-frequency (TF) representation (TFR) of nonstationary signals composed of multiple components with slow varying instantaneous frequency (IF). However, for signals composed of multiple components with fast varying IF, SST still suffers from TF blurs. In this paper, we introduce a time-frequency analysis (TFA) method called matching synchrosqueezing transform (MSST) that achieves a highly concentrated TF representation comparable to the standard TF reassignment methods (STFRM), even for signals with fast varying IF, and furthermore, MSST retains the reconstruction benefit of SST. MSST captures the philosophy of STFRM to simultaneously consider time and frequency variables, and incorporates three estimators (i.e., the IF estimator, the group delay estimator, and a chirp-rate estimator) into a comprehensive and accurate IF estimator.

In this paper, we first introduce the motivation of MSST with three heuristic examples. Then we introduce a precise mathematical definition of a class of chirp-like intrinsic-mode-type functions that locally can be viewed as a sum of a reasonably small number of approximate chirp signals, and we prove that MSST does indeed succeed in estimating chirp-rate and IF of arbitrary functions in this class and succeed in decomposing these functions. Furthermore, we describe an efficient numerical algorithm for the practical implementation of the MSST, and we provide an adaptive IF extraction method for MSST reconstruction. Finally, we verify the effectiveness of the MSST in practical applications for machine fault diagnosis, including gearbox fault diagnosis for a wind turbine in variable speed conditions and rotor rub-impact fault diagnosis for a dual-rotor turbofan engine.

1. Introduction

Machine fault diagnosis in industrial systems is a very active field of research, which is aimed to ensure safety, minimize breakdowns and following impact upon performance, reduce maintenance costs, and improve production efficiency achieved through the implementation of condition monitoring [1–4]. Among the various techniques, vibration-based

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Nomenclature

Abbreviations

EEMD	ensemble empirical mode decomposition
EMD	empirical mode decomposition
FFT	fast Fourier transform
GD	group delay
HHT	Hilbert-Huang transform
HPR	high-pressure rotor
IF	instantaneous frequency
LPR	low-pressure rotor
MIF	matching instantaneous frequency
MSST	matching synchrosqueezing transform
RMS	root mean square
RSTFT	reassigned short-time Fourier transform
SM	S-method
SNR	signal-to-noise ratio
SST	synchrosqueezing transform
STFRM	standard time-frequency reassignment method
STFT	short-time Fourier transform
TF	time-frequency
TFA	time-frequency analysis
TFR	time-frequency representation
WT	wavelet transform

Symbol notations

t, u	time variable
ω, ξ	frequency variable
s	scale variable
$g(t)$	window function for STFT
$\psi(t)$	wavelet function for WT
$W_x^{\psi}(u,s)$	WT of signal x with wavelet ψ
$P_x^{\psi}(t,s)$	scalogram of signal x with wavelet ψ
$\hat{\omega}_x(u,s)$	IF estimator for reassigned scalogram
$\hat{t}_x(u,s)$	GD estimator for reassigned scalogram
$\hat{P}_x^{\psi}(t,\omega)$	reassigned scalogram
$S_x^g(u,\xi)$	STFT of signal x with window g
$P_x^g(t,\xi)$	spectrogram of signal x with window g
$\hat{\omega}_x(u,\xi)$	IF estimator for reassigned spectrogram
$\hat{t}_x(u,\xi)$	GD estimator for reassigned spectrogram
$\hat{P}_x^g(t,\omega)$	reassigned spectrogram
$ITFR_x(t,\omega)$	ideal TF representation,
$\tilde{\omega}_x(u,s)$	IF estimator for WT-based SST and MSST
$\tilde{t}_x(u,s)$	GD estimator for WT-based MSST
$\tilde{c}_x(u,s)$	chirp-rate estimator for WT-based MSST
$\tilde{\omega}_x^m(u,s)$	MIF estimator for WT-based MSST
$\tilde{\omega}_x(u,\xi)$	IF estimator for STFT-based SST and MSST
$\tilde{t}_x(u,\xi)$	GD estimator for STFT-based MSST
$\tilde{c}_x(u,\xi)$	chirp-rate estimator for STFT-based MSST
$\tilde{\omega}_x^m(u,\xi)$	MIF estimator for STFT-based MSST
$T_x(u,\omega)$	SST result
$T_{x,\tilde{\varepsilon}}^{\delta}(u,\omega)$	SST result with threshold $\tilde{\varepsilon}$ and accuracy δ
$T_x^m(u,\omega)$	MSST result
$T_{x,\tilde{\varepsilon}}^{m,\delta}(u,\omega)$	MSST result with threshold $\tilde{\varepsilon}$ and accuracy δ

methods are one of the most suitable and effective ways and thus have been widely studied and applied in rotating machine fault diagnosis [5–11]. However, nonstationary operating conditions [12], particularly varying running speed [13] and varying load [14], result in the challenge of extracting effective features from complex vibration signals [15].

Some interesting researches related to machine fault diagnosis under nonstationary operating conditions have been studied recently in the literature. Pichler et al. introduced a classification strategy for detecting cracked or broken valves in reciprocating compressors under varying load conditions, and the method's performance was validated by real world