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A fuzzy clustering method for periodic data, applied for processing turbomachinery beamforming maps

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ABSTRACT

In the present paper, the fuzzy c-means method is extended, and an algorithm is proposed for fuzzy clustering of data lying in a feature space of arbitrary dimensions, with one of them being periodic. To aid in determining the optimal number of clusters, the Xie-Beni validity index is extended, to account for the periodicity. Furthermore, the relative weights of the dimensions in the calculation of distances are investigated. The method is incorporated into a procedure for processing turbomachinery beamforming maps. Thus, an objective, robust way of identifying the sound sources being present in such machines is obtained. These properties are ensured by selecting the required parameters through parameter studies. Presented through a case study, the method is used to determine the most significant sound source mechanisms in an axial fan.

1. Introduction

The noise emitted by turbomachinery is a serious issue. To reduce it, the noise generation mechanisms have to be identified, understood, and controlled. Acoustic beamforming can effectively be used for indicating the areas where the strongest sources of noise are present [1–3]. Some approaches can handle rotating systems [4–7], enabling the investigation of turbomachinery. Beamforming measurements are often carried out on aero-engines due to noise emission limits becoming more strict. In the recent years, investigation of low-speed axial fans has begun, as they operate in larger numbers and closer to people [8–10]. Combined with empirical analysis and numerical simulations, as done in Refs. [11–15], the information regarding source locations can aid in understanding noise generation mechanisms. Then an iterative redesign process can be started, within which, by modifying the blade geometry, the noise emission can be reduced.

The results of beamforming are usually presented in the form of contour maps over the target, in the present case, over the rotor. These are called *beamforming maps*. These maps are usually interpreted visually. This process however includes subjective elements. Furthermore, such maps are usually generated for several frequency bands, in which case, drawing conclusions based on them is even more difficult.

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Nomenclature

Latin letters

a	element of the weighting matrix
$\mathbf{A}$	weighting matrix
B	number of fan blades
c	number of fuzzy clusters
d	distance metric
D	number of data set dimensions
f	frequency
i	index of data points
$\mathbf{I}$	identity matrix
j	index of clusters
J	clustering objective function
k	period tracking variable
l	running index
m	fuzzifier
N	number of all data points to be clustered
p	dimensionless amplitude
$\mathbf{p}$	periodic offset vector
P	period
R	dimensionless radius
s	iteration step
w	membership value
$\mathbf{x}$	generic vector
$\mathbf{y}$	generic vector

Greek letters

β	angular position of base source
γ	arbitrary periodic quantity
ϵ	exit criterion residual
$\boldsymbol{\mu}$	cluster centre
σ	cluster amplitude
$\boldsymbol{\xi}$	data point for clustering

Superscripts and subscripts

A	weighted using matrix $\mathbf{A}$
min	minimum
max	maximum
P	periodic distance measure
T	transpose

Abbreviations

AMP & ADC	Amplifier and analogue-to-digital converter
FCM	Fuzzy c-means clustering
FCM4DD	Fuzzy c-means clustering for directional data
LE	Leading edge
PAM	Phased array microphone
PC	Personal computer
ROSI	Rotating source identifier
SPL	Sound pressure level
TE	Trailing edge
XB	Xie-Beni index

Others

$\hat{\square}$	normalised to the 0 … 1 range

The situation is further complicated by the presence of point spread functions in the maps. Due to these, a point-like source appears with a spatial extension, and close-by sources become difficult to separate. Furthermore, peaks may appear at locations where in reality no sources are present. These effects are usually treated using deconvolution methods, such as CLEAN-SC [16] or DAMAS [17], however, in some cases, these algorithms may not be applicable. Yet, the aforementioned problems have to be tackled in some way.

To do that, a novel algorithmic processing method was proposed in Refs. [18,19]. It aimed at the identification of noise generation mechanisms through a data reduction and clustering procedure. This was illustrated in a case study, and found adequate, however, still contained a subjective choice due to the periodicity of the blading.

The main contribution of the present paper is to introduce a method for fuzzy clustering, applicable when one of the dimensions of the data set has periodic attributes. This is applied for the analysis of turbomachinery beamform maps as part of the aforementioned algorithm [19], aimed at objective and reproducible identification of noise source mechanisms. The extended algorithm is applied onto the beamform maps of an axial fan, to identify the dominant noise generating mechanisms.

In the present application, the novel procedure ensures that clustering takes the periodicity of the blade passages into account, even if only one blade passage is used for data analysis. However, it may be applied for any kind of data, where a periodic dimension is present.

The structure of the paper is as follows. First, the complete method for source identification is described. Second, the original fuzzy clustering algorithm is presented, the meaning and the difficulty of clustering in the presence of periodic dimensions is explained, and the modified clustering algorithm is introduced. Third, details about the case study are given. Fourth, the results of applying the new algorithm onto the beamforming data are presented and compared to those of the previous method. Finally, the conclusions of the work are summarised.

2. Noise source identification method

To investigate and analyse turbomachinery noise, a novel algorithmic approach was proposed in Refs. [18,19]. It aimed at identifying broadband noise generation mechanisms in an axial fan, in an objective manner. The method was designed to decrease the effects of both measurement noise and side lobes, without deconvolution. The reason for omitting deconvolution methods was that a microphone array with generic microphone placement was used in the measurements, and thus the beamform maps were created using the Rotating Source Identifier (ROSI) [4]. As this method does not provide a cross spectral