A new grey relational model based on discrete Fourier transform and its application on Chinese marine economic

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Abstract

Purpose – The traditional grey relational models directly describe the behavioural characteristics of the systems based on the sample point connections. Few grey relational models can measure the dynamic periodic fluctuation rules of the objects, and most of these models do not have affinities, which results in instabilities of the relational results because of sequence translation. The paper aims to discuss these issues.
Design/methodology/approach – Fourier transform functions are used to fit the system behaviour curves, redefine the area difference between the curves and construct a grey relational model based on discrete Fourier transform (DFTGRA).
Findings – To verify its validity, feasibility and superiority, DFTGRA is applied to research on the correlation between macroeconomic growth and marine economic growth in China coastal areas. It is proved that DFTGRA has the superior properties of affinity, symmetry, uniqueness, etc., and wide applicability.
Originality/value – DFTGRA can not only be applied to equidistant and equal time sequences but also be adopted for non-equidistant and unequal time sequences. DFTGRA can measure both the global relational degree and the dynamic correlation of the variable cyclical fluctuation between sequences.

Keywords Grey relational analysis, Marine economic, Discrete Fourier transform

Paper type Research paper

1. Introduction

1.1 The grey relational degree

Grey relational analysis (GRA) is an important branch of grey systems theory and the basis of grey systems analysis, modelling, forecasting and decision making. The basic idea is to determine the relational degree according to the degree of similarity between time series polyline or curve of each factor in the system. The more similar the polylines or curves, the greater is the relational degree between factors and vice versa.

Deng (1989) pioneered the theory of grey correlation. Subsequent variations on the original were then proposed by different scholars. These include the grey absolute correlation model (Mei, 1992), T-type correlation model (Tang, 1995), B-type correlation model (Wang, 1989), C-type correlation model (Zhao and Wang, 1999) and slope correlation model (Dang *et al.*, 2004), etc. In recent years, there are still various scholars improving and proposing new model variants based on the original. Zhang *et al.* (2011) proposed the

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GRA-AR correlation model that considers absolute and relative differences based on Deng's model. Xie and Liu (2011) proposed the grey geometric correlation model. Liu *et al.* (2006, 2011) constructed the grey absolute association model and the grey correlation degree of the similarity perspective based on the whole directed area of the broken line enclosed graph. Shi *et al.* (2008, 2010) constructed grey period correlation degree based on similarity vision and grey amplitude correlation degree. Zhang *et al.* (2014) proposed a new grey projection correlation model using the vector projection principle. To investigate the trends' similarity of sequence dynamic changes, Li *et al.* (2015) proposed the grey change rate correlation degree to measure the similarity of the change rate.

By virtue of the sustained promotion of grey theory, it has gradually been extended to three-dimensional space. Zhang and Liu (2010) used panel data in three-dimensional space as application background and proposed the multidimensional correlation degree that extended the grey absolute correlation degree based on matrices. Wu *et al.* (2013) proposed a novel grey convex relational degree in the context of three-dimensional panel data based on the grey convex relational degree for two-dimensional data and an approximation of the Hessian matrix for discrete sequences. Qian *et al.* (2013) constructed a grey matrix correlation analysis model which can be used to measure the similarity of multi-index panel data. Liu *et al.* (2014) used the grid method to describe the geometric characteristics of panel data in three-dimensional space and constructed a grid correlation coefficient, deriving a grey grid relational degree model according to the arithmetic mean. Li *et al.* (2015) integrated the three-level difference information of deviation, difference and separation to construct an index correlation analysis model. Cui and Liu (2015) expanded the GRA from the traditional vector space to matrix space and proposed a grey matrix similarity relational model for panel data contexts. Wu *et al.* (2016) constructed similarity and proximity models based on the angle and distance of space vectors, based again on panel data.

In recent years, many scholars had carried on the comprehensive comparison and analysis combining GRA with other methods (Yamaguchi *et al.*, 2007; Zhu and Hipel, 2012; Yang *et al.*, 2014; Wang *et al.*, 2016). In addition, as grey relational theory has matured and been widely used in many fields such as economics, social sciences, industrial applications, agriculture, mining, transportation, education, medicine, ecology, water conservation, geology, aerospace, and so on. Luo *et al.* (2002) applied grey relational theory to investment decision making and verified the effectiveness of applying grey system theory to uncertain information systems. Despite its complexity, Zhang *et al.* (2007) established a model of employee performance evaluation based on GRA, improving on shortcomings in existing performance evaluation methods. Chen *et al.* (2008) introduced an improved GRA method into supply chain risk assessment and established an appropriate evaluation model. Zheng *et al.* (2014) used B-type absolute correlation to recognise cancerous hepatic cells. Zhu *et al.* (2014) proposed the assignment strategy of grey entropy correlative fitness value by combining the grey relational degree analysis and the information entropy theory. He applied this method to difference and genetic algorithms to solve the problem of flow shop scheduling. Jiang and Gao (2015) established four grey correlation models between real estate and other industries. Abudukeremu *et al.* (2015) exploited GRA to evaluate hydrogen evolution performance of eight different non-precious metal alloy cathodes. Pandey and Panda (2015) used GRA to facilitate the optimisation of multiple quality characteristics in bone drilling. Nelabhotla *et al.* (2016) applied Taguchi-based grey relational analysis (TGRA) to the optimisation of chemical mechanical planarization process-parameters of c-plane gallium-nitride (GaN) in potassium-permanganate/alumina ($KMnO_4/Al_2O_3$) slurry. Wang and Dong (2016) tested the GRA theory against a case study of cost optimisation in mining. Dixit *et al.* (2016) used a grey relational grade method to compare two different rapid prototyping systems based on dimensional performance.

1.2 Macroeconomic growth and marine economic growth

In the twenty-first century, many coastal countries and regions attach great importance to the formulation of marine strategic plans, the marine economic development as an important strategic direction. The USA has formulated the "21st Century Blueprint" and the "US Marine Action Plan" and so on, for the US Government in the next few years to make a comprehensive deployment of the marine development strategies. Canada has also introduced the Canadian Ocean Strategy and the Canadian Ocean Action Plan. Russia has also strengthened the deployment of the marine strategy, developed the "Russian Federation to the 2020 marine policy"; South Korea introduced the "South Korea 21st Century Ocean" national strategy, through the development and use of the ocean, make the better development of marine economy, to be a super ocean country. These countries attach great importance to the development of marine development strategies and marine economic development.

For China, China's "Twelfth Five-Year Plan" developed the marine economy into an economy of national strategic importance. Its "Thirteenth Five-Year Plan" emphasises the expansion of blue economic space, with further development of marine economy, with the objective of increasing the proportional contribution of gross ocean product (GOP) to gross domestic product (GDP). In March 2016, China proposed the "21st Century Maritime Silk Road Construction". In essence, this aims to promote the development of marine economy. According to preliminary accounting, China GOP growth rate increased 8.1 per cent on average. In 2015, China GOP amounted to 6,466.9bn yuan, of which 3,899.1bn yuan was added to marine industries and 2,567.8bn yuan will be added to marine-related industries. Thus, marine economy is becoming a new economic growth engine for China and worthy of increased attention to harness this growth.

Economic growth is an important research topic in macroeconomics. When economic growth is affected by endogenous and exogenous shocks, fluctuations in economic development are difficult to avoid, and such fluctuations tend to have some inherent regularity. The twenty-first century is the era of the ocean. Whether and how the development of marine economy will be influenced by various factors is fluctuating, including whether and how it is consistent with the trends in overall macroeconomic growth. These are questions worth exploring.

At present, there are relatively few studies on the relation between marine economy and macroeconomics, and most of them are limited to the promotion and contribution of marine economy to the national economy. There are also some studies on the relationship between marine economy, marine industries and economy in a certain area. Kildow and Mcllgorm (2010) analysed problems in the development of marine economy and expounded its importance to the development of the wider national economy. Yan (2011) used grey correlation theory to establish a positive correlation between marine industries and economic growth, again for a case study in Zhejiang Province. Karyn *et al.* analysed the value of the 2007 multi-sectoral marine business activities in Ireland. Fu (2011) analysed coupling and coordination of marine industry agglomeration *vis-à-vis* the regional economy by applying coupling degree and coupling coordination degree methodologies. Kwaka *et al.* analysed the impact of marine industries on the national economy using input–output analysis. Karyn and Cathal studied the relation between the Irish marine economy and regional economic development. They argued that the importance of marine development to regional economic development was seriously neglected, despite their results illustrating co-dependencies to the extent that the marine economy could promote the development of the regional economy. Li *et al.* (2013) used the location quotient to calculate the degree of marine industry agglomeration in Zhejiang Province and analysed the promotion effect of marine industry agglomeration on the regional economy of that area. According to the Granger causality test in a panel data context, Ji and Liu established that the marine industry cluster has a clear and evident effect on China coastal economy while the promotion effect of the coastal economy on the marine industrial cluster was not significant. Qin *et al.* (2013)

used the Yangtze River Economic Belt as a case study, and based on a GRA, they delineated the relation between the watershed economy and the marine economy. Yin *et al.* (2013) studied the fluctuation characteristics and developmental trends of the total marine economy and the major marine industries. Jiang *et al.* (2014) used a multi-factor production function model to deduce the contributions of the elements of the marine economy to regional economic growth in China. Zhao and Cao (2014) analysed the external and internal linkage effects of the land and sea industries in Shandong Province using the grey correlation degree methodology, the contribution rate of output value and the industrial fluctuation coefficient. Xu *et al.* (2014) analysed the impact of Zhejiang's marine economy on regional economic development from 2001 to 2010 and studied the corresponding relation between marine industrial structure change and regional economic growth. Zhang and Xiong (2015) determined that the influence of marine industry structural change on the regional economy of Zhejiang Province became more pronounced when subjected to cointegration analysis and VEC modelling.

1.3 Research motivation and content

GRA models reflect more true relational degree between system factors, have different applications in the social economy and production practice. However, there are some shortcomings in traditional grey relational models, such as the GRA models based on areas, when the time series is shifted, the overall shape has not changed but the relational degree has changed, and the property of affinity is absent. Further, the GRA model is based on the size of the area between the broken lines, it can only reflect the close degree of time series to a certain extent and cannot show fluctuation specificities nor truly reflect the characteristics of the sequences. In addition, most existing correlation models only apply for equidistant or equal time sequences with very limited application. To overcome these shortcoming, we, first, propose a grey relational model based on the discrete Fourier transform (DFTGRA), DFTGRA not only applies to non-equal-length or non-equidistant sequences, but also reflects the characteristics of the variable cycle fluctuations, and has an affine property.

Furthermore, it is of great significance to explore the relationship between marine economic growth and macroeconomic growth and their respective fluctuation rules, which make decision makers have a better understanding of the marine economy development. Such explanations can also provide a theoretical basis for future development of both the marine and national economies. But the relation between the marine economy and macro-economy has focussed on a subset of this dynamic system, principally the relation between marine industries and economic growth. There is little research on the relation between the marine economy and economic growth.

Besides, China marine economic development started late, statistics of marine economic data is not standardized, there are some missing data, some relevant data are difficult to obtain, marine economic statistics with typical "limited sample, poor information" features. The traditional correlation analysis methods need a lot of statistical data, the little data are not enough to find the statistical rules; Fortunately, GRA is insensitive to sample size and rules.

In summary, we choose DFTGRA here to study the relation between China marine economy and macroeconomic growth. DFTGRA is applied to the dynamic correlation analysis of marine economy and macroeconomic growth in China coastal provinces, which provides a theoretical and scientific basis for the relevant departments to have a profound understanding of the dynamic relationship between marine economic growth and economic growth. There is a better understanding of marine economy and its relationship to macroeconomics.

In the following sections, this study describes the theoretical basis of the discrete Fourier transform (DFT) and illustrates the deficiencies of the existing relational model. Subsequently, DFTGRA is established and its properties are propounded (Section 2).

Next, DFTGRA is used to explore the dynamic correlation between marine economy and macroeconomic growth in China coastal provinces. It further reveals the correlation effect of marine economy and regional economic growth in five typical coastal provinces and cities in China, and validates the effectiveness, feasibility and superiority of DFTGRA (Section 3). The study concludes by summarizing significant findings and describing topic areas for future research (Section 4).

2. Grey relational model based on DFT

2.1 DFT model

DFT is the effective method of signal analysis, pertaining to time-frequency signal change studies. Here, we extend application of the DFT to a new field, which transforms the discrete time series into a continuous form, that is, a trigonometric function is used to fit the time series to better reflect the fluctuation specificities of the time series, applicable in the context of unbalanced time intervals.

Given a time series: $X = \{x(1), \ldots, x(T)\}$, $x(t) \in R$, $1 \leqslant t \leqslant T$. It will be approximated by $F_A(t)$, and the function is composed of a set of trigonometric functions, as follows:

$$F_A(t) = \sum_{k=0}^{K} \beta_k f_k(t), \quad t = 1, \ldots, T, \tag{1}$$

where $f_k(t)$ is a trigonometric basis vector, which is a set of orthogonal basis. Like:

$$f_k(t) = \begin{cases} \sin \frac{k+1}{2}\omega t, & k \text{ is odd} \\ \cos \frac{k}{2}\omega t, & k \text{ is even} \end{cases}, \tag{2}$$

where β_k is the amplitude, and impacts the trigonometric function of the longitudinal expansion; ω the cycle, and impacts the trigonometric function of the horizontal expansion.

Based on the characteristics of small grey samples, and assuming $2K+1 \leqslant n$, where n is the sample size. If $K=4$, then:

$$f_0(t) = 1, \; f_1(t) = \sin \omega t, \; f_2(t) = \cos \omega t, \; f_3(t) = \sin 2\omega t, \; f_4(t) = \cos 2\omega t.$$

2.2 Regression model solution

For time series $X = \{x(1), \ldots, x(T)\}$, our goal is to recover regression coefficients (β_0, β_1, β_2, β_3, β_4). According to the regression model:

$$\begin{pmatrix} x(1) \\ \vdots \\ x(T) \end{pmatrix} = \begin{pmatrix} 1 & \sin \omega & \cos \omega & \sin 2\omega & \cos 2\omega \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & \sin T\omega & \cos T\omega & \sin 2T\omega & \cos 2T\omega \end{pmatrix} \begin{pmatrix} \beta_0 \\ \vdots \\ \beta_4 \end{pmatrix}.$$

The matrix form is denoted by $X = A\beta$.

Using the least squares method, that is, to find β, let:

$$\min (X - A\beta)^T (X - A\beta).$$

By the existence of extreme conditions, $\left(\partial(X - A\beta)^T (X - A\beta)\right)/(\partial\beta) = 0$ is established. Solution:

$$\beta = \left(A^T A\right)^{-1} A^T X. \tag{3}$$

2.3 Calculation of the correlation coefficient and the correlation degree

For two time series $X = \{x(1), \ldots, x(T)\}$ and $Y = \{y(1), \ldots, y(T)\}$, respectively, conduct regression analysis based on trigonometry by the least squares method to obtain the best fit function:

$$F_A(t) = \alpha_0 + \alpha_1 \sin \omega t + \alpha_2 \cos \omega t + \alpha_3 \sin 2\omega t + \alpha_4 \sin 2\omega t, \tag{4}$$

$$F_B(t) = \beta_0 + \beta_1 \sin \omega t + \beta_2 \cos \omega t + \beta_3 \sin 2\omega t + \beta_4 \sin 2\omega t, \tag{5}$$

where $F_A(t)$ and $F_B(t)$ are used to express the discrete time series as continuous functions. The sequence information is retained, and the similarity of time series is transformed into the similarity of two continuous functions as shown below.

Figure 1 illustrates two random time series. For measuring their similarity, to adhere to the requirements depicted in Figure 2, we analyse the relational degree after obtaining the fitted curve. In the traditional sense, the measuring similarity of two-dimensional time series mainly considers distances, slopes, areas, and so on. In this study, we redefine a correlation measure based on areas.

The traditional analysis based on the area correlation works as follows (as shown in Figure 2), we obtain the area difference of graph AGHC and DGHF by integral, as the relational coefficients of the corresponding moment. Next, the relational degree is defined according to the absolute correlation formula. However, the defined relational degree is not affine. That is, to a certain extent, the translation of time series X, graph AGHC area will change (upward translation, the area becomes large; otherwise, becomes small), Y remains constant. Although there is no change in shape, it is simple to transform; the correlation degree will change, possibly substantially. To solve this problem, we define the relational degree based on the area difference between graph ABC and DEF, as follows:

Definition 1. Suppose the time series $X = \{x(1), \ldots, x(T)\}$ and $Y = \{y(1), \ldots, y(T)\}$, the time series is fitted to establish $F_A(t)$ and $F_B(t)$, calculate the areas $S_{X_i} = \int_{t_i}^{t_i+\Delta t} F_A(t)dt - F_A(t_i) \cdot \Delta t$ and $S_{Y_i} = \int_{t_i}^{t_i+\Delta t} F_B(t)dt - F_B(t_i) \cdot \Delta t$, standardise to remove magnitude effects using functions of maxima

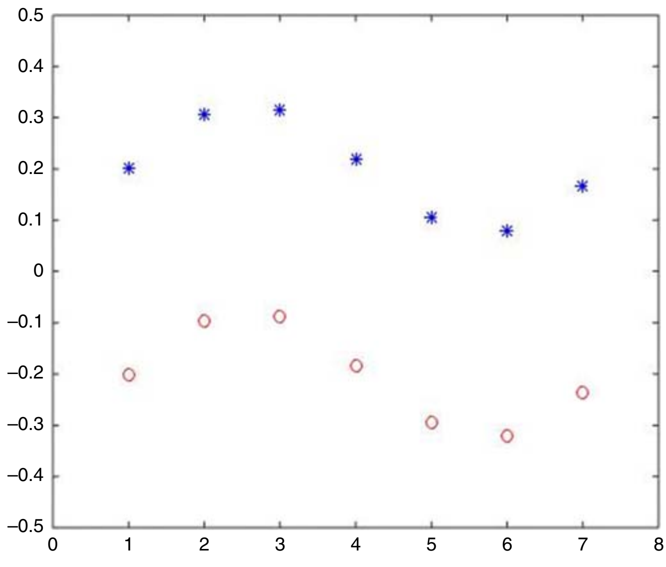

Figure 1.
Time series scatter diagram

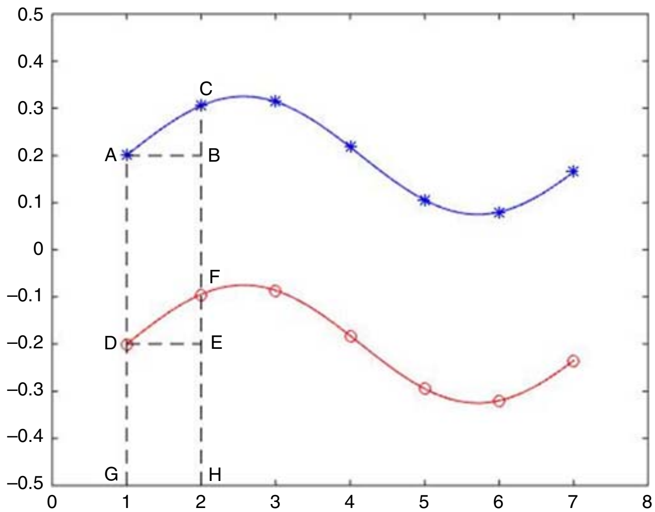

Figure 2.
Time series function fitting

and minima: $S'_{X_i} = (S_{X_i})/(\max S_{X_i} - \min S_{X_i})$, $S'_{Y_i} = (S_{Y_i})/(\max S_{Y_i} - \min S_{Y_i})$. The area difference is $\Delta S_i = |S'_{X_i} - S'_{Y_i}|$ (ΔS_i is the corresponding area after eliminating the magnitude, $i = 1, 2 \ldots, T-1$):

$$\varepsilon_i = \frac{1}{1+\Delta S_i}, \tag{6}$$

is known as the grey correlation coefficient of time series, X and Y.

Definition 2. Suppose two time series are $X = \{x(1), \ldots, x(T)\}$ and $Y = \{y(1), \ldots, y(T)\}$:

$$\varepsilon = \frac{1}{T-1}\sum_{t=1}^{T-1} \varepsilon_i, \tag{7}$$

is known as the grey relational degree based on DFT.

2.4 Properties of DFTGRA model

Theorem 1. DFTGRA model has the following properties:

(1) Normative: $0 < \varepsilon \leqslant 1$, $\varepsilon = 1 \Leftarrow X(t) = Y(t)$, $\Delta S_i \in [0, +\infty)$ is clearly established.

(2) Symmetry: $\Delta S_i = \left|S'_{X_i} - S'_{Y_i}\right| = \left|S'_{Y_i} - S'_{X_i}\right|$, according to the definition of grey relational degree is clearly established.

(3) Uniqueness: the grey relational degree is determined by two sequences. Once the sequence is determined, the corresponding area difference between the two sequences is also determined, and the grey relational degree is determined.

(4) Comparability: nature (4) is obtained by the nature (3).

Theorem 2. Assume the reference sequence is $X = \{x(1), \ldots, x(T)\}$, The relative sequence of the relevant factors is $Y_i = \{y_i(1), \ldots, y_i(T)\}$ and $Y_j = \{y_j(1), \ldots, y_j(T)\}$, the grey correlation degree is ε. If the inequality $\varepsilon_{XY_i} > \varepsilon_{XY_j}$ holds, we contend that factor Y_i is superior to factor Y_j, Recorded as $Y_i \succ Y_j$, where $\succ$ is the grey relational order derived from the grey relational degree ε.

(1) Isotonicity; the grey relational order derived from DFTGRA has the property of preserving order, that is $Y_i \succ Y_j$, if Y_l, $Y_i \succ Y_j$ is established.

Proof. By property (3), we determine that DFTGRA degree is unique and the theorem is proved. ∎

Theorem 3. For the reference sequence $X = \{x(1), \ldots, x(T)\}$ and the comparative sequence $Y = \{y(1), \ldots, y(T)\}$, after a DFT, we establish the functions $F_A(t)$ and $F_B(t)$. When $F_A(t) = F_B(t) + C$(C is a constant.). If $\varepsilon(X), Y) = 1$, the correlation model comprises affinities: it can be said that the two sequences are parallel.

Proof:

$$
\begin{aligned}
S_{X_i} &= \int_{t_i}^{t_i+\Delta t} F_A(t)dt - F_A(t_i)\cdot\Delta t \\
&= \int_{t_i}^{t_i+\Delta t} (F_B(t)+C)dt - (F_B(t_i)+C)\cdot\Delta t \\
&= \int_{t_i}^{t_i+\Delta t} F_B(t)dt + \int_{t_i}^{t_i+\Delta t} Cdt - F_B(t_i)\cdot\Delta t - C\cdot\Delta t \\
&= \int_{t_i}^{t_i+\Delta t} F_B(t)dt + C\cdot(t_i+\Delta t - t_i) - F_B(t_i)\cdot\Delta t - C\cdot\Delta t \\
&= \int_{t_i}^{t_i+\Delta t} F_B(t)dt - F_B(t_i)\cdot\Delta t \\
&= S_{Y_i},
\end{aligned}
$$

so $S_{X_i} = S_{Y_i}$.

Similarly, $\max S_{X_i} = \max S_{Y_i}$, $\min S_{X_i} = \min S_{Y_i}$.

Dimensionless processing: $S'_{X_i} = (S_{X_i})/(\max S_{X_i} - \min S_{X_i})$, $S'_{Y_i} = (S_{Y_i})/(\max S_{Y_i} - \min S_{Y_i})$,

so $S'_{X_i} = S'_{Y_i}$; according to formula (6) and (7):

$$
\Delta S_i = \left| S'_{X_i} - S'_{Y_i} \right| = 0 \Rightarrow \varepsilon_i = \frac{1}{1+\Delta S_i} = 1 \Rightarrow \varepsilon = \frac{1}{T-1}\sum_{t=1}^{T-1} \varepsilon_i = 1 \Rightarrow \varepsilon(X, Y) = 1.
$$

That is, the correlation coefficient ε_i and the correlation degree ε are both 1, so the two sequences are parallel, and the DFTGRA model has the property of affinity. ∎

2.5 The steps based on DFTGRA model

(1) Conduct qualitative analysis on the reference sequence X_0, and determine the comparative sequence X_i.

(2) According to the formulas (1) and (2), set appropriate Fourier transform functions based on the reference and comparative sequences and construct the corresponding regression models.

(3) Calculate the OLS regression coefficients using formula (3) and obtain the corresponding time series regression functions.

(4) According to the reference sequence and the comparative sequence regression functions, use a definite integral, and determine the area difference of each corresponding interval.

(5) According to formulas (6) and (7), calculate the correlation coefficients and correlation degree of both the reference and comparative sequences.

(6) According to the correlation order of reference sequence and comparative sequence, obtain the quantising relations of the correlation degree between the variation trends of these sequences. Finally, analyse and infer relevant conclusions combining the practical situation of study members (Figure 3).

3. Empirical analyses

Economic cycle fluctuations have always been a paramount importance question in macroeconomics. International scholars use GDP or the long-term trend deviation degree to measure macroeconomic fluctuations. The twenty-first century is the century of the ocean, but there are few studies on the fluctuation of the ocean economy, and less on the correlation between marine economy and macroeconomic fluctuations. On the basis of macroeconomic cycle theories, we systematically analyse the evolution rules of marine economic development in China and use GOP to describe the status and trends of marine economic cycle fluctuations. Simultaneously, we analyse the relation between economic and marine economic growth rates with a view to providing a new basis for researching these interactions in China.

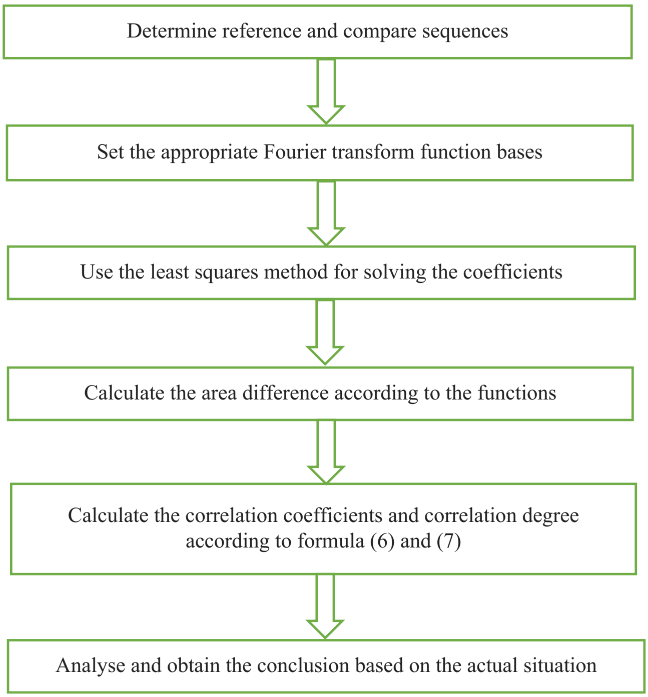

Figure 3.
The steps diagram of DFTGRA model

We select GOP as an aggregate indicator to reflect the level of monetized ocean goods and services. GDP is chosen as an aggregate indicator to reflect the economic status of the national economy. We use the data on these indicators for the following typical coastal provinces: Shanghai, Tianjin, Guangdong, Shandong and Fujian. Further provincial level data are sourced from *China Marine Statistical Yearbook*, *China Statistical Yearbook* and *Regional Statistical Yearbook*. For implementing our methodology, the raw data are processed and growth rates are determined for GDP and GOP across the five provinces, then we use the DFTGRA model to analyse these data as described below. Due to the incomplete statistics, the GOP data of Tianjin in 2015 are lack (Tables I–V).

According to the DFT, the fitting function is:

$$f(t) = a_0 + a_1 \cos \omega t + b_1 \sin \omega t + a_2 \cos 2\omega t + b_2 \sin 2\omega t + a_3 \cos \omega t + b_3 \sin 3\omega t. \quad (8)$$

Using the least squares method, the Fourier transform function coefficients are obtained by MATLAB software (the confidence level is 95%).

3.1 Dynamic relational analysis GDP and GOP growth rates in China

Characteristics of marine economy differ by region, resources, space and the land–ocean development model. This gives rise to unique fluctuations in this marine economic context. Further, the marine and land economies have a strong relation in terms of symbiosis and correlation (Figure 4). Namely, relative to macroeconomic fluctuations, marine economic fluctuations observe an evident synchronicity. According to this synchronization effect, we research this dynamic relation in recent years, which provides a theoretical basis for the regulation of both the macro-economy and marine economy.

According to formula (6) and function (8), we recover the annual correlation coefficients for GDP and GOP growth rates in China.

According to Figures 4 and 5, the dynamic relation between China GDP growth rate and GOP growth rate also testifies to a certain volatility, rather than being wholly deterministic. The correlation degree is at its minimum in 2007, which may be caused by methodological changes about GOP statistics in 2006. To eliminate the impact of statistical variations, we divided the 2003–2015 sample into two time periods. Before 2006, relational fluctuations are relatively large, which indicates that the development of the marine economy is not completely influenced by the macro-economy. In other words, macroeconomic growth does not necessarily wholly drive the growth of the marine economy that is affected by other factors such as national marine regulation policy, marine technology, marine disasters, etc. After 2007, the relational volatility is smaller and there is an overall de-growth trend, which means that the economic downturn has had certain inhibitory effects on the development of the marine economy. Therefore, the development of the macro-economy and its interaction mechanisms with the development of the marine economy is a problem worth studying. China GDP and GOP growth form a dynamic system. With the development of the system and, concomitantly, the change of the data increase, the relational degree is constantly changing. This change reflects system-level developments and it is, therefore, pertinent for decision makers to adjust and control the system effectively, which illustrates the practical significance of this enquiry. In addition, results of the dynamic relational analysis are consistent with the growth trend of both marine economies and macroeconomic, which testifies to the utility of the DFTGRA model.

3.2 Dynamic correlation analysis of GDP and GOP growth rates in typical provinces

Coastal areas are heterogeneous with respect to locational advantage, marine economic development, marine economic development strategy, etc. Therefore, the overall vitality of

	China		Shanghai		Tianjin		Guangdong		Shandong		Fujian	
	GDP	GOP	GDP	GOP	GDP	GOP	GDP	GOP	GDP	GOP	GOP	GDP
2001	5,210.12	9,518.4	5,210.12	624.93	1,919.09	268.65	12,039.25	1,542.69	9,195.04	840.58	4,072.85	684.08
2002	5,741.03	11,270.5	5,741.03	721.96	2,022.6	416.08	13,502.42	1,693.71	10,275.5	994.61	4,467.55	1,037.08
2003	6,694.23	1,1952.3	6,694.23	845.91	2,386.94	568.07	15,844.64	1,936.09	12,078.15	1,477.64	4,983.67	1,344.96
2004	8,072.83	14,662.0	8,072.83	1,956.58	3,110.97	1,051.47	18,864.62	2,975.5	15,021.84	1,938.46	5,763.35	1,738.08
2005	9,247.66	17,655.6	9,247.66	2,296.45	3,697.62	1,447.49	22,557.37	4,288.39	18,366.87	2,418.11	6,554.69	1,503.79
2006	10,572.24	21,592.4	10,572.24	3,988.2	4,344.27	1,369	26,587.76	4,113.9	21,900.19	3,679.3	7,583.85	1,743.1
2007	12,494.01	25,618.7	12,494.01	4,321.4	5,252.76	1,601	31,777.01	4,532.7	25,776.91	4,477.8	9,248.53	2,290.3
2008	14,069.87	29,718.0	14,069.87	4,792.5	6,719.01	1,888.7	3,6796.71	5,825.5	30,933.28	5,346.3	10,823.01	2,688.2
2009	15,046.45	32,277.6	15,046.45	4,204.5	7,521.85	2,158.1	39,492.52	6,661	33,896.65	5,820	12,236.53	3,202.9
2010	17,165.98	39,572.7	17,165.98	5,224.5	9,224.46	3,021.5	46,036.25	8,253.7	39,169.92	7,074.5	14,737.12	3,682.9
2011	19,195.69	45,496.0	19,195.69	5,618.5	11,307.28	3,519.3	53,246.18	9,191.1	45,361.85	8,029	17,560.18	4,284
2012	20,181.72	50,045.2	20,181.72	5,946.3	12,893.88	3,939.2	57,147.75	10,506.6	50,013.24	8,972.1	19,701.78	4,482.8
2013	21,602.12	54,313.2	21,602.12	6,305.7	14,442.01	4,554.1	62,474.79	11,283.6	55,230.32	9,696.2	21,868.49	5,028
2014	23,567.7	59,936.0	23,567.7	6,217	15,726.93	5,027	67,809.85	13,500	59,426.59	10,400	24,055.76	6,500
2015	24,964.99	64,669.0	24,964.99	6,347	16,538.19	–	72,812.55	15,200	63,002.3	11,000	25,979.82	7,000

Table I.
GDP and GOP in China and the typical provinces (100m yuan)

Table II.
Growth rates of GDP and GOP in China and typical provinces

	China		Shanghai		Tianjin		Guangdong		Shandong		Fujian	
	GDP Growth rate	GOP Growth rate	GDP Growth rate	GOP Growth rate	GDP Growth rate	GOP Growth rate	GDP Growth rate	GOP Growth rate	GDP Growth rate	GOP Growth rate	GDP Growth rate	GOP Growth rate
2002	0.0973	0.1841	0.1019	0.1553	0.0539	0.5488	0.1215	0.0979	0.1175	0.1832	0.0969	0.5160
2003	0.1286	0.0605	0.1660	0.1717	0.1801	0.3653	0.1735	0.1431	0.1754	0.4856	0.1155	0.2969
2004	0.1768	0.2267	0.2059	1.3130	0.3033	0.8510	0.1906	0.5369	0.2437	0.3119	0.1564	0.2923
2005	0.1567	0.2042	0.1455	0.1737	0.1886	0.3766	0.1958	0.4412	0.2227	0.2474	0.1373	−0.1348
2006	0.1709	0.2230	0.1432	0.7367	0.1749	−0.0542	0.1787	−0.0407	0.1924	0.5216	0.1570	0.1591
2007	0.2314	0.1865	0.1818	0.0835	0.2091	0.1695	0.1952	0.1018	0.1770	0.2170	0.2195	0.3139
2008	0.1818	0.1600	0.1261	0.1090	0.2791	0.1797	0.1580	0.2852	0.2000	0.1940	0.1702	0.1737
2009	0.0912	0.0861	0.0694	−0.1227	0.1195	0.1426	0.0733	0.1434	0.0958	0.0886	0.1306	0.1915
2010	0.1831	0.2260	0.1409	0.2426	0.2264	0.4001	0.1657	0.2391	0.1556	0.2155	0.2044	0.1499
2011	0.1840	0.1497	0.1182	0.0754	0.2258	0.1648	0.1566	0.1136	0.1581	0.1349	0.1916	0.1632
2012	0.1033	0.1000	0.0514	0.0583	0.1403	0.1193	0.0733	0.1431	0.1025	0.1175	0.1220	0.0464
2013	0.1009	0.0853	0.0704	0.0604	0.1201	0.1561	0.0932	0.0740	0.1043	0.0807	0.1100	0.1216
2014	0.0818	0.1035	0.0910	−0.0141	0.0890	0.1038	0.0854	0.1964	0.0760	0.0726	0.1000	0.2928
2015	0.0638	0.0790	0.0593	0.0209	0.0516	–	0.0738	0.1259	0.0602	0.0577	0.0800	0.0769

Coefficients	a_0	a_1	b_1	a_2	b_2	a_3	b_3
China							
GDP	0.1427	−0.04808	0.006666	−0.01764	−0.01307	−0.01618	0.01456
GOP	0.1478	−0.03499	0.036	−0.01961	0.002233	0.03125	−0.00192
Shanghai							
GDP	−7,393,000	11,020,000	1,285,000	−4,323,000	−1,022,000	697,100	253,100
GOP	0.2274	−0.04473	0.2838	−0.2219	−0.03255	−0.01897	−0.0532
Tianjin							
GDP	0.1757	−0.05767	0.008312	−0.04561	−0.00211	−0.03429	−0.02052
GOP	0.2419	0.05395	0.1359	−0.03679	0.1889	−0.09751	−0.01231
Guangdong							
GDP	0.1386	−0.03132	0.04046	−0.02451	0.002581	0.001236	0.01186
GOP	0.1934	−0.0194	0.06739	−0.1083	0.01915	0.05077	−0.09974
Shandong							
GDP	0.08363	−0.03947	0.09058	−0.03911	0.08521	0.01569	0.05028
GOP	2,479,000,000	3,714,000,000	178,900,000	−1,480,000,000	−142,900,000	245,300,000	35,670,000
Fujian							
GDP	0.1532	−0.0004132	−0.03588	0.02232	0.00377	0.01224	−0.03286
GOP	−3,873,000,000	5,802,000,000	−311,800,000	−2,312,000,000	249,200,000	382,700,000	−62,180,000

Table III. Coefficients of the Fourier transform fitting functions

	China		Shanghai		Tianjin		Guangdong		Shandong		Fujian	
	GDP	GOP	GDP	GOP	GDP	GOP	GDP	GOP	GDP	GOP	GDP	GOP
ω	0.4811	0.4391	0.01451	0.4731	0.4827	0.4082	0.4562	0.5122	0.2354	0.005168	0.6227	−0.00744

Table IV. Periodic coefficients ω of the Fourier transform model

Years	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Coefficients	0.7038	0.8780	0.7241	0.8790	0.6421	0.8349	0.7382	0.7908	0.8172	0.7805	0.8666	0.7301	0.9454

Table V. Relational coefficients between China GDP and GOP growth rates

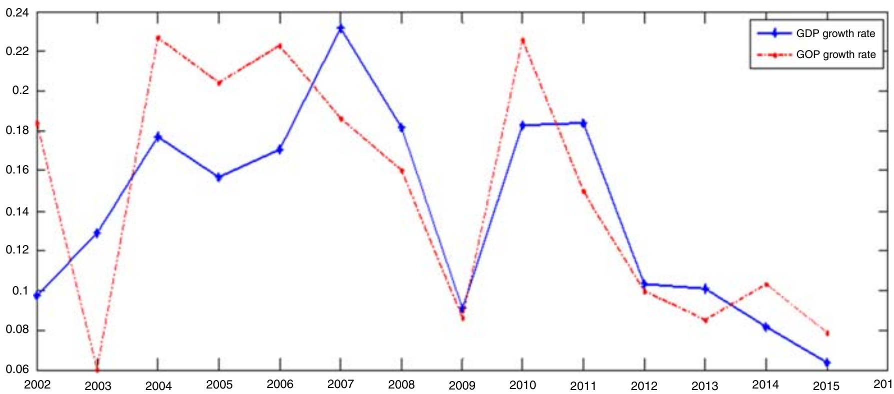

Figure 4. The growth rates of China GDP and GOP

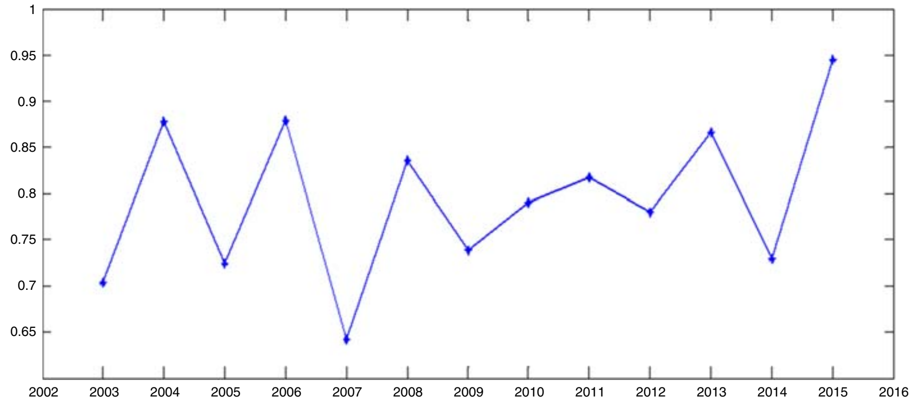

Figure 5.
Temporal trends in GDP–GOP correlation coefficients for China

the marine economy exhibits regional variation. According to the characteristics of objective economic parameters in the marine economy and cyclic fluctuations in these parameters, we selected five typical provinces and cities: Shanghai, Tianjin, Guangdong, Shandong and Fujian to analyse the relation between GDP and GOP growth rates for comparative analysis.

According to formula (6) and function (8), the correlation coefficients between the annual growth rate of GDP and GOP are calculated for these five typical provinces and cities (Table VI).

According to Figure 6, the dynamic relation in Shanghai is stable and maintained at relatively low levels. Similarly, according to Figure 7, Shanghai's economic growth has also

Table VI.
Relational coefficients between GDP and GOP growth rates in the five typical provinces

Years	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Shanghai	0.3517	0.3613	0.3168	0.2832	0.2852	0.3130	0.3424	0.3603	0.3741	0.3808	0.3736	0.3770	0.4313
Tianjin	0.9074	0.7617	0.7718	0.7545	0.7755	0.9641	0.7385	0.8374	0.8294	0.8609	0.7671	0.7190	0.8615
Guangdong	0.8129	0.8602	0.8043	0.6325	0.9740	0.5671	0.6741	0.7782	0.7777	0.7444	0.6656	0.9282	0.8744
Shandong	0.8327	0.6949	0.5887	0.5374	0.5354	0.5749	0.6443	0.7177	0.7604	0.7641	0.7610	0.7958	0.9146
Fujian	0.8233	0.7356	0.9682	0.7963	0.7064	0.7250	0.6468	0.9304	0.7788	0.4997	0.5957	0.6869	0.5388

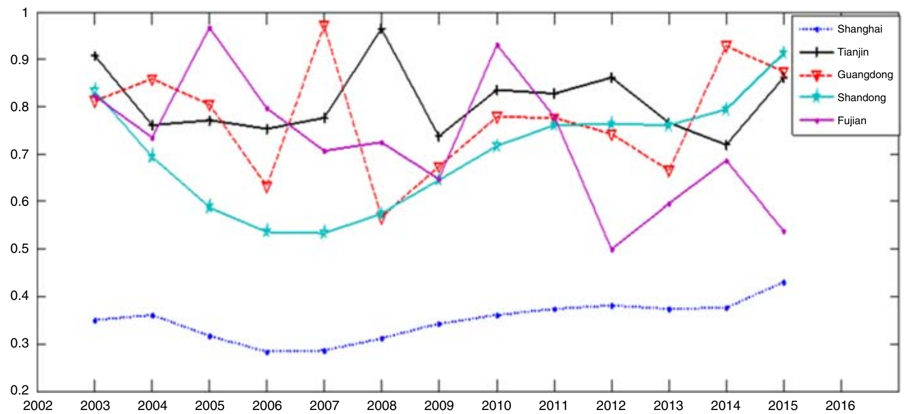

Figure 6.
Temporal trends in GDP–GOP relational coefficients for the five provinces

been relatively stable over time. However, the marine economy fluctuated significantly before 2011, after 2011, it is similar with economic growth, the relational degree has increasing trend between them. The intrinsic effect of both is worth exploring. The dynamic correlation of Tianjin between 2007 and 2009 is relatively large, possibly because of statistics methodological changes. Outside of this time period, the correlation is relatively high and stable. This suggests that in Tianjin, the macro-economy has a substantial impact on the marine economy. The dynamic correlation in Guangdong and Fujian fluctuated substantially because they are relatively open systems and are vulnerable to the influence of exogenous shocks. In addition, marine disasters in Guangdong and Fujian occurred frequently, which hinders growth of marine economy. The relation in Shandong observes a downward trend before 2006, after which this trend reverses. This suggests that macroeconomic effects on the marine economy are large and varied. According to the results of the dynamic correlation analysis, there is significant regional variation in terms of the impact of the macro-economy on the marine economy. Therefore, relevant policy interventions by decision-making institutions will be adjusted to local conditions, which makes each region macro-economy and marine economic develop faster and better. In addition, it is concluded that the model results are consistent with empirically derived expectations, proving its effectiveness.

3.3 Correlation analysis between GDP and GOP growth rates in typical provinces and cities

According to formula (7), the relational coefficients between the growth rate of GDP and ocean GDP of the five typical provinces and cities are recovered (Table VII). In order to draw the trend figure, the GOP of Tianjin in 2015 is supplemented by the growth rate average.

According to Table VII, $\varepsilon_2 > \varepsilon_3 > \varepsilon_5 > \varepsilon_4 > \varepsilon_1$, that is to say, the relational degree between the growth rate of GDP and GOP in Tianjin is the largest; Guangdong is second, Fujian and Shandong rank third and fourth, respectively, Shanghai is at the minimum.

In Figure 7, the marine economic development trend of Shanghai is volatile while its macro-economy is smoother. From the analysis of China macro-economy, Shanghai is consistently the pioneer of China economic development, enjoying all kinds of preferential policies and “try first” conditions. As a consequence, these factors promote the

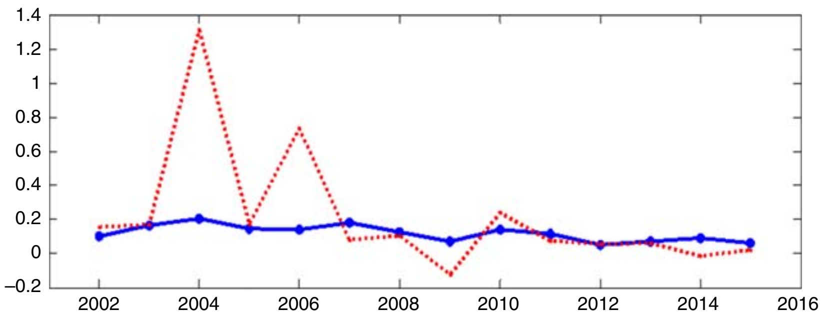

Figure 7. The trend of two growth rates in Shanghai

Table VII. Relational degree between GDP and GOP growth rates in five provinces

Provinces	Shanghai ε_1	Tianjin ε_2	Guangdong ε_3	Shandong ε_4	Fujian ε_5
Correlation degree	0.3501	0.8115	0.7765	0.7017	0.7255

macroeconomic development of Shanghai, but at the same time, it affects the stability of Shanghai marine economy development. According to the illustrated trends, the growth rates of GDP and GOP in Shanghai are dissimilar; hence, the correlation degree of Shanghai represents the regional minimum.

In Figure 8, although Tianjin's marine economic fluctuation is relatively volatile, it is similarities with the macroeconomic trend and, as previously reported, represents the maximum regional correlation. Tianjin, as a municipal city under the central government, has unique history, nature, environment, society, economy and other advantages. However, its marine economic development is still faced with many challenges, such as resources bottleneck, environmental capacity, then arrow hinterland, and many other issues, so its marine economic development is unstable, lack of the power of constantly development. From the macro-level analysis, Tianjin, as a municipal city under the central government, has important policy support from multiple branches of the state marine administration and benefits from a new development on the coast. Since 2005, Tianjin's new coastal area was incorporated into a national development strategy, and being a national key support development district, it has enjoyed even more policy support than the Shanghai free trade zone, significantly boosting the development of marine economy in Tianjin and exerting important influences on marine economic fluctuations.

In Figure 9, the growth rate of GDP and GOP is broadly the same in Guangdong province, but the volatility is more severe in the marine economy; its relational degree ranks second. Guangdong, as a strong economic province and characterised as an open system, is relatively vulnerable to internal and external factors and the double competition pressures

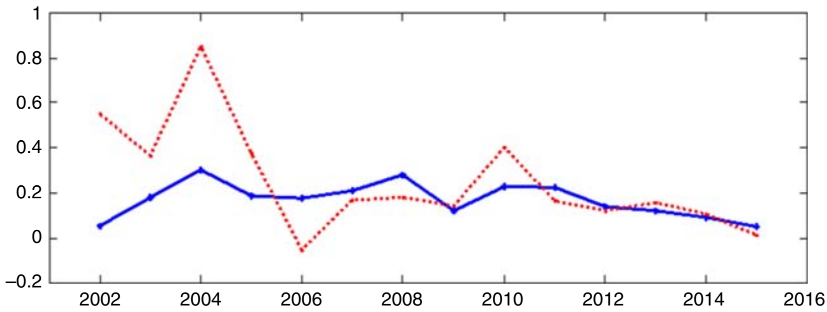

Figure 8.
The trend of two growth rates in Tianjin

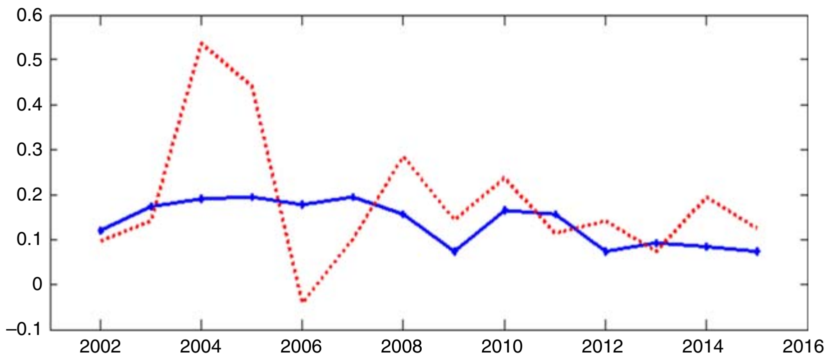

Figure 9.
The trend of two growth rates in Guangdong

from international and domestic forces. There is no doubt that all these factors compound the fluctuations to the Guangdong marine economy, but the overall macroeconomic impact on marine economy is relatively large.

In Figure 10, the growth rate of GOP is not particularly stable in Shandong province, but the macroeconomic situation is relatively stable. Shandong, as a large ocean province, is rich in marine resources. Marine economic development started early, and the scale of the marine economy reflects this, but marine contribution to the overall economy is still small in proportional terms. Poor management in terms of resources consumption and the marine economic development model significantly affect the viability of the marine economic system. Thus, the correlation is relatively small, only ranking fourth.

In Figure 11, marine economic fluctuation characteristics in Fujian are relatively apparent. Between 2002 and 2007, marine economic volatility is substantial, while relatively stability is observed outside of this period. Fujian marine economic development started relatively early. Basic conditions and its geographical position are superior although the natural environment of Fujian is relatively fragile. Marine natural disasters occur frequently. The macroeconomic scale is limited. These problems all affect the rapid development of the marine economy. According to observations, the two curves trend, in the middle time, is relatively consistent, but in other years, there are obvious differences, so the relational degree is medium, ranking third.

In summary, the relational analysis results are consistent with actual growth rate movements, which illustrates the effectiveness of the DFTGRA model. But overall, the macroeconomic trend is downward in recent years, which may be caused by the 2007–2009 financial crisis. To a certain extent, this crisis also affected the growth of marine economy, although the specific mechanisms of impact require further study.

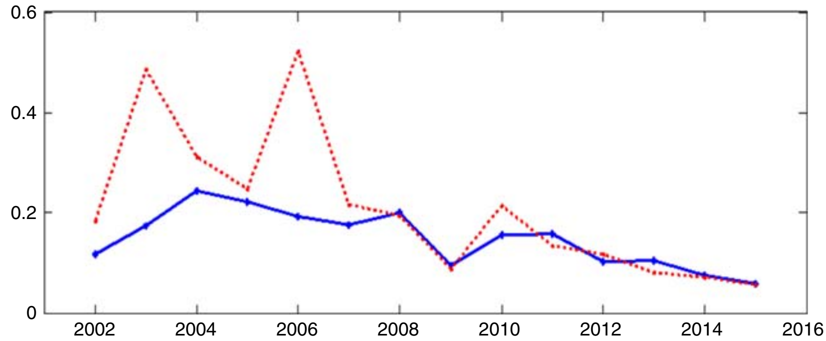

Figure 10.
The trend of two growth rates in Shandong

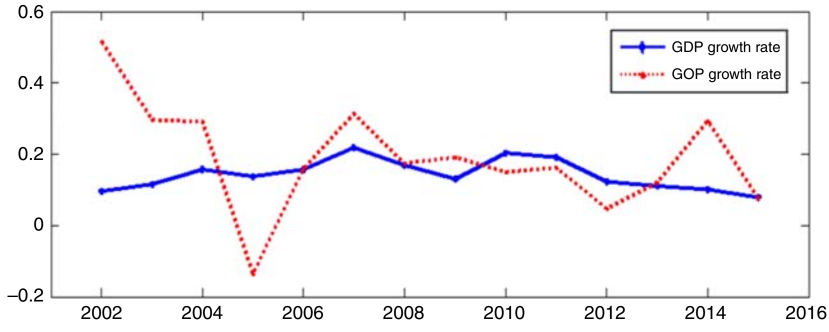

Figure 11.
The trend of two growth rates in Fujian

3.4 Comparative analysis with traditional grey relational methods

We choose the traditional Deng's correlation model (DGRA) (Deng, 1989) and the slope correlation model (SGRA) (Dang *et al.*, 2004) to compare and analyse the relation between the five typical provinces and cities' macroeconomic and marine economic growth rates and rank them accordingly (Table VIII). The GOP of Tianjin in 2015 is supplemented by the growth rate average in the DGRA model and SGRA model (Table IX).

According to the ranking results, it can be concluded that the relational degree is different across the GDP and GOP growth rates in the five typical provinces and cities. The similarity of the close perspective is considered in the DGRA model. The proximity of Shanghai and Shandong is comparatively large, as is the correlation. The proximity degree of Fujian and Tianjin rank third and fourth, respectively; Guangdong is close to the extent of the smaller, the smallest relational degree. The SGRA model considers the similarity of the trend perspective. Shandong and Guangdong, especially post-comparison, are similar to the trend, followed by Tianjin and Fujian and then by Shanghai, where the relational degree is smallest, with similarity in this respect being apparent only between 2011 and 2013. Relational degree ranks are therefore different by different perspectives. In terms of DGRA model, the trend similarity cannot be considered. Whereas for SGRA model, the proximity cannot be considered. For the fluctuate sequence, the similarity of the fluctuation degree cannot be well reflected from the perspective of the proximity and the trend similarity, and the DFTGRA model makes up for this deficiency. Different relational models have different applicability, and DFTGRA is more suitable than other models for the relational analysis of sequences exhibiting volatility.

4. Conclusion and prospect

The traditional GRA model is based on the "limited sample poor information" grey system. By virtue of the little data, the trajectory of the system behaviour approaches the broken line, the error is relatively large; the traditional GRA models do not have the affine property. Therefore, DFTGRA is proposed. According to the fluctuation of time series, the model uses the Fourier transform to obtain the curve which describes the behavioural characteristics of the system. Then, the correlation coefficient is calculated by the newly defined area difference using integration. Next, DFTGRA degree is defined, and the properties and

Table VIII. Grey correlation degrees according to different methods

	DFTGRA degree	DGRA degree	SGRA degree
Shanghai	0.3501	0.8393	0.4358
Tianjin	0.8115	0.7160	0.5867
Guangdong	0.7765	0.6678	0.6027
Shandong	0.7017	0.7903	0.7350
Fujian	0.7255	0.7295	0.5682

Table IX. Method-based ranking of regions

	DFTGRA degree	DGRA degree	SGRA degree
Shanghai	5	1	5
Tianjin	1	4	3
Guangdong	2	5	2
Shandong	4	2	1
Fujian	3	3	4

scopes of application are discussed. DFTGRA solves the shortcomings of existing grey relational degree and overcomes the problem of non-equidistance and unequal time intervals. It also better reflects the fluctuations of the objects. Finally, DFTGRA is applied to the study of the relationship between the growth rate of GDP and GOP in China. Compared with empirical data and the results of other GRA models, which illustrates that the model is valid and feasibility, in addition, it reflects the scope of the model application, and the superiority of the model.

In summary, there are significant differences for the driving forces of marine economy and regional economic development in different areas. In some provinces, the marine economy and regional economic development work synergistically and promote each other; some is still relatively small, which should cause the relevant areas to have great focus. They should learn development measures from the high performing coastal provinces and cities, combining with their own marine economic development characteristics and development advantages, facilitate marine economy comprehensive and rapid development, and ultimately contribute to stable long-term growth of macroeconomic and marine economy.

DFTGRA requires further improvement in future, and is tested in different domains for more suitable areas and typical systems research, to more fully verify its effectiveness. And we also can be more in-depth study of the fluctuations rule in the cycle, as well as the lag or synchronization relationship between the objects. At the same time, contrast analysis according to different fitting methods (e.g. cubic spline interpolation fitting, Lagrange difference fitting, and so on) should be further explored *vis-à-vis* their relative advantages and disadvantages.

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