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Resonant R&D structure for effective technology development amidst megacompetition—an empirical analysis of smart cooperative R&D structure in Japan's transport machinery industry

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Abstract

Under the megacompetition in globalizing economy while facing long lasting economic stagnation, the effective utilization of potential resources for innovation has become a crucial strategy for R&D intensive industries. The construction of a smart cooperative R&D structure has thus become significant. Among Japan's R&D intensive industries, the transport machinery industry has constructed an effective cooperative R&D structure by smartly complementing both comparatively advantageous and disadvantageous technologies by means of integrating the effective utilization of technology spillover and joint collaborative R&D.

Prompted by this complementing system, this paper attempts to elucidate the mechanism enabling the transport machinery industry to construct the smart cooperative R&D structure. Resonant R&D structure is identified as a source of such R&D cooperation leading to increasing its marginal productivity of technology.

Keywords: R&D cooperation; Outsourcing; Business cycles; Resonance

1. Introduction

1.1. Effective cooperative R&D structure as a survival strategy amidst megacompetition

A dramatic surge in information technology (IT) around the world and evolving globalizing economy in the 1990s are subjecting firms to megacompetition. Difficulties in financing R&D activities due to long lasting economic stagnation compel industries to construct an effective cooperative R&D structure as demonstrated in Fig. 1.

Fig. 1 illustrates the trend in the dependency on outsourced R&D in total R&D expenditure in the Japanese manufacturing industry, which demonstrates that the average increase rates of the dependency over the periods 1968–1978, 1979–1990 (after the second energy crisis and before the bursting of the bubble economy[1]) and 1991–2000 (after the bursting of the bubble economy) are 6.81% p.a. (per annum), 0.02% p.a. and 3.81% p.a., respectively. While the trend in the dependency on outsourced R&D stagnated during the period of the 1980s after the energy crises, it changed to an increasing trend again in the 1990s. This increasing trend demonstrates the significance of the cooperative R&D in Japan's manufacturing industry corresponding to the foregoing circumstances amidst megacompetition.

The construction of such a cooperative R&D structure is particularly crucial for R&D intensive manufacturing industries as demonstrated in Fig. 2.

Looking at Fig. 2, we note that R&D intensive sectors share higher dependency on outsourced R&D.

[1] In the latter half of the 1980s, the Japanese economy entered a spiral of spending and investment speculations that brought about an unsustainable economic bubble during which land and stock prices rose more than three to five times within a span of 5 years. The boom is exemplified in financial investment, especially in land and stocks, that provided investors a myth that their assets had ballooned, resulting in less investment in technology and capital. This phenomenon, referred to as Japan's 'bubble economy', started in 1987 and lasted until the 1990s.

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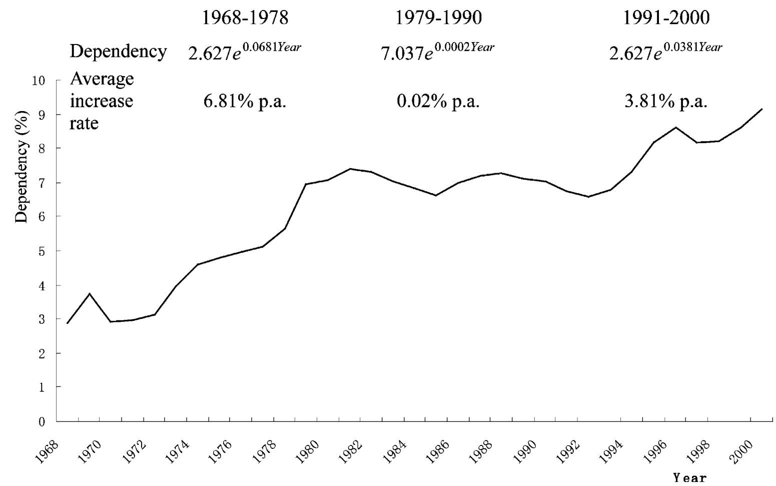


Fig. 1. Trend in the dependency on outsourced R&D in the Japanese manufacturing industry (1968–2000). (a) The dependency on outsourced R&D (DOR) is measured by the ratio of expenditure on outsourced R&D and total R&D. (b) $\ln(\text{DOR}) = 0.9659_{(21.51)} + 0.0681D_1\ \text{Year}_{(10.24)} + 0.0002D_2\ \text{Year}_{(20.25)} + 0.0381D_3\ \text{Year}_{(21.85)} + 0.9853D_{2(0.05)}$ (adj. $R^2 = 0.956$, DW = 1.41), where dummy variables $D_1 = 1$ for 1968–1979; $D_2 = 1$ for 1980–1989; and $D_3 = 1$ for 1990–2000. Figures in parentheses indicate *t*-statistic, all significant at the 1% level. *Source*: Statistical Bureau, Management and Coordinating Agency (1968–2000). (The Management and Coordinating Agency was renamed the Ministry of Public Management, Home Affairs, Posts and Telecommunications after Japan's government restructuring in 2001.).

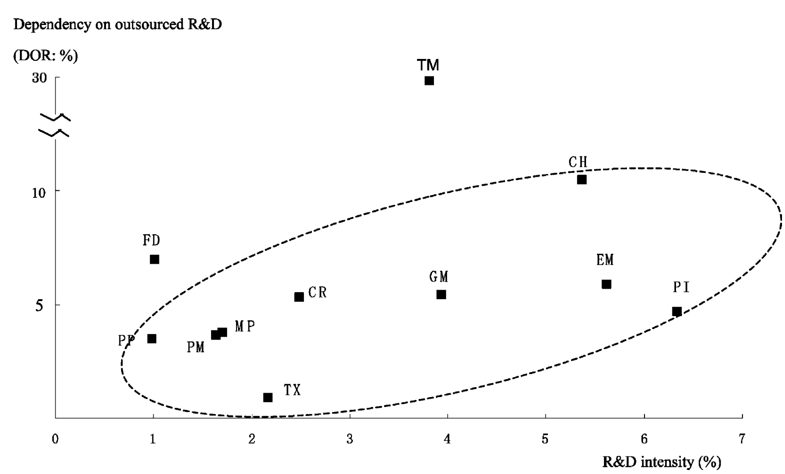


Fig. 2. R&D intensity and dependency on outsourced R&D in Japan's manufacturing industry (2000). (a) $\text{DOR} = -0.51 + 1.60\ (\text{R\&D intensity})_{(1.84)^{*}} + 14.91D_{\text{TM\&FD}(3.58)^{**}}$ (adj. $R^2 = 0.549$, DW = 1.87). Taking into account the unique cooperative R&D structure of TM and FD, dummy variable $D_{\text{TM\&FD}}$ (TM and FD = 1, other sectors are 0) is used for the analysis. Figures in parentheses indicate *t*-statistic: ** Significant at the 1% level; * significant at the 10% level. (b) FD: food; TX: textiles; PP: pulp and paper products; CH: chemicals; CR: ceramics; PM: primary metals; MP: metal products; GM: general machinery; EM: electrical machinery; TM: transport equipment; PI: precision instruments. *Source*: Statistical Bureau, Ministry of Public Management, Home Affairs, Posts and Telecommunications (2001).

This is conspicuous in five R&D intensive sectors as listed in Table 1, particularly the transport equipment sector (TM). Since these sectors in Table 1 are ranked the top five with respect to R&D intensity, construction of the effective cooperative R&D structure is indispensable for their survival strategy amidst megacompetition.

Looking at Table 1, we note that these five sectors' share amounts to 85.0% of R&D expenditure in Japan's manufacturing industry. In addition, their R&D intensity levels are higher than the average level of the manufacturing industry. Thus, their R&D activities have played a significant role in stimulating technology initiative in Japan's manufacturing industry, leading to improving its international competitiveness amidst megacompetition.

1.2. *Smart cooperative R&D structure of transport machinery industry*

Focusing on R&D activities of these five R&D intensive sectors, in order to compare the effectiveness of

Table 1
R&D intensive sectors in Japan—top five in 2000

	Chemicals (CH)	General machinery (GM)	Electrical machinery (EM)	Transport equipment (TM)	Precision instruments (PI)	Manufacturing industry as a whole (MA)
R&D intensity (%)	5.36	3.93	5.65	3.90	6.34	*3.70*
R&D expenditure (billion yen)	16 259	8836	37 987	15 526	4869	*98 160*
Share[a]	(16.6%)	(9.0%)	(38.7%)	(15.8%)	(5.0%)	[*85.0%*]

The figure in the square bracket indicates the sum of the share of the five sectors. *Source*: Statistical Bureau, Ministry of Public Management, Home Affairs, Posts and Telecommunications (2001).

[a] Share indicates the percentage of each sector's R&D expenditure in the manufacturing industry.

Table 2
Comparison of marginal productivity of technology in Japan's five R&D intensive sectors (1987–1999)

	CH	GM	EM	TM	PI
$\frac{(\partial \bar{V}/\partial T)_{1991-1999}}{(\partial \bar{V}/\partial T)_{1987-1990}}$	$\frac{0.532}{0.177}=4.56$	$\frac{0.250}{-0.100}$	$\frac{0.798}{0.292}=2.73$	$\frac{0.580}{0.007}=78.68$	$\frac{-0.062}{0.276}$
$(\partial \bar{V}/\partial T)_{1991-1999}-(\partial \bar{V}/\partial T)_{1987-1990}$	0.415	0.350	0.506	0.573	0.338

cooperative R&D structure, first, the marginal productivities of technology are compared[2] by contrasting the periods of the bubble economy (1987–1990) and after its bursting (1991–1999). The results are summarized in Table 2 by both the ratio of the average marginal productivities of technology of the post-burst period and during the bubble economy as well as the balance of the average marginal productivities of technology between the two periods compared.

Looking at Table 2, we note that TM demonstrates a conspicuous achievement in improving its marginal productivity by both the ratio and the balance.

Another noteworthy feature of TM can be identified by its conspicuously high dependency on outsourced R&D as observed in Fig. 2. Fig. 3 highlights this conspicuous interactive R&D structure of TM by comparing the share of R&D funds received and paid outside among five R&D intensive sectors in 1990 and 2000. The share of R&D funds paid outside in Fig. 3 is equivalent to the R&D outsourcing ratio in Fig. 2.

Fig. 3 demonstrates that TM has maintained the highest level of R&D funds both received and paid outside. Particularly, it demonstrates a conspicuously high level of R&D funds paid outside. This can be justified by its convergent structure of internal R&D demonstrated by the entropies[3] of both internal R&D by product field and specialty of regular researcher as demonstrated in Fig. 4. Looking at Fig. 4, we note that both entropies of TM are the lowest among the five sectors examined, which implies that TM's internal R&D has converged into its own field.

This convergence has been complemented by procuring R&D in other fields than its own. Conspicuously high dependency on outsourced R&D by paying high rate of R&D funds outside as demonstrated in Figs. 2 and 3 is considered to be a consequence of this complement. Thus, TM seems to have constructed an elaborate interactive R&D structure leading to improving its marginal productivity of technology by converging its own R&D on its competent field, providing its own

[2] The source of the decrease in the Japanese manufacturing industry's competitiveness in the 1990s can be attributed to its dramatic decrease in marginal productivity of technology. Total factor productivity (TFP) growth rate can be decomposed as follows (see Appendix B):

$$\frac{\Delta \mathrm{TFP}}{\mathrm{TFP}}=\frac{\partial V}{\partial T}\cdot\frac{R}{V}$$

where $\partial V/\partial T$ is marginal productivity of technology; and R/V, R&D intensity. Japan's manufacturing industry demonstrated contrasting decrease in its marginal productivity of technology from 0.945 in the 1980s to −0.316 in the 1990s as follows:

	$\frac{\Delta \mathrm{TFP}}{\mathrm{TFP}}$ (% p.a.)	$=\frac{\partial V}{\partial T}\cdot\frac{R}{V}$ (%)
1985-1990	2.61	0.945·2.76
1990-1995	−0.39	−0.136·2.84

[3] The entropy ε is defined as follows: $\varepsilon=-\sum_{i=1}^{n}p_i\ln p_i$, where p_i is the share of ith component in total, and n is the number of components. If the share is completely concentrated on one field, the entropy is 0. If equally distributed, the entropy is $\ln n$. As a result, the range of entropy is $0\le\varepsilon\le\ln n$.

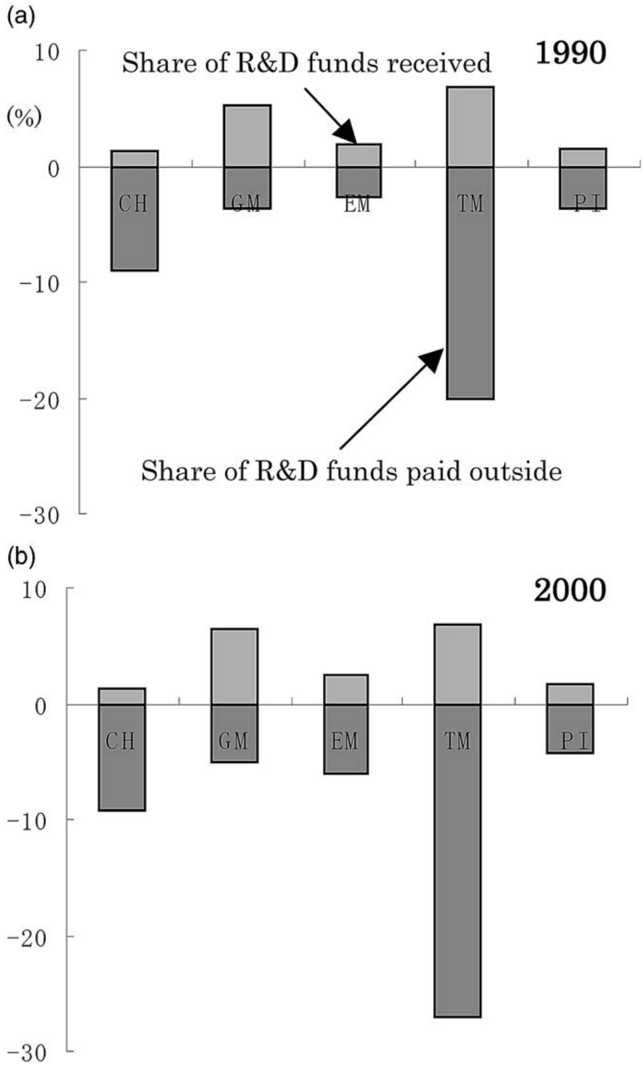


Fig. 3. Share of R&D funds received and paid outside. Outside implies external institutes (firms, universities and research institutes) of firms. *Source*: Statistical Bureau, Ministry of Public Management, Home Affairs, Posts and Telecommunications (1991, 2001).

competent technology to other sectors and actively introducing external technology from other sectors.

These conspicuous achievements of TM with respect to its improvements in marginal productivity of technology together with interactive R&D structure prompt us to investigate the possibility that TM has been constructing a smart cooperative R&D structure by integrating (i) assimilation of less advantageous matured technology spilled over from other sectors, and (ii) joint collaboration with certain sectors on comparative advantageous innovative technology.

Given that the effective cooperative R&D structure is a crucial survival strategy for R&D intensive industries amidst megacompetition, TM's smart cooperative R&D structure provides constructive suggestions for their survival strategies.

1.3. Identification of the mechanism leading to a smart cooperative R&D structure—resonant cooperative R&D structure

Prompted by these postulates, this paper conducts an empirical analysis focusing on the trend in TM's cooperative R&D structure over the last three decades, and attempts to identify the mechanism that leads to the construction of a smart cooperative R&D structure.

Not a few works have analyzed economic resonance for the identification of the mechanism leading to an effective economic cooperation. In international economics, it is often considered that economic linkage such as bilateral trade has spurred interactions between two economies leading to economic resonance between them. Modeling of co-movements in different countries' business cycles as multivariate systems with common dynamic factors has been attempted by Gregory et al. (1997) as well as Anderson and Vahid (1998). Gerlach (1988) and Baxter and Stockman (1989) analyzed the impacts of different exchange rate regimes on the volatility of output. Some of these works were prompted by the observation of similar periodic nature of economic performance between different countries. Goodwin (1947) first applied the idea of dynamic coupling in his analysis of these economic resonance phenomena in international economies. Anderson and Ramsey (2002) in their recent work analyzed dynamic coupling between the US and Canadian industrial productions and identified an increased degree of oscillation in the equilibrium paths and greater synchronization between the two economies. These works suggest that the resonance between different sectors linked with TM may play a key role for the foregoing smart cooperative R&D structure. However, while some works attempted to apply these analyses to techno-economic analysis, they remain conceptual ones and no research has been conducted to analyze the resonant structure of R&D cooperation.

In this paper, as suggested by the pioneer works investigating economic resonance by identifying similar periodic nature of economic performance between different countries, spectral analysis and vector autoregression (VAR) analysis are introduced. In order to identify TM's resonance with other sectors, first, sectors having the same periodic nature are selected to verify the significance of their impacts on TM's cooperative structure. Spectral analysis is introduced to identify the periodic nature of cooperative R&D leading to the construction of resonant structure. Second, aiming at confirming significance of the resonance between selected sectors with the same periodic nature, VAR analysis is attempted. Since VAR analysis employs exogenous as

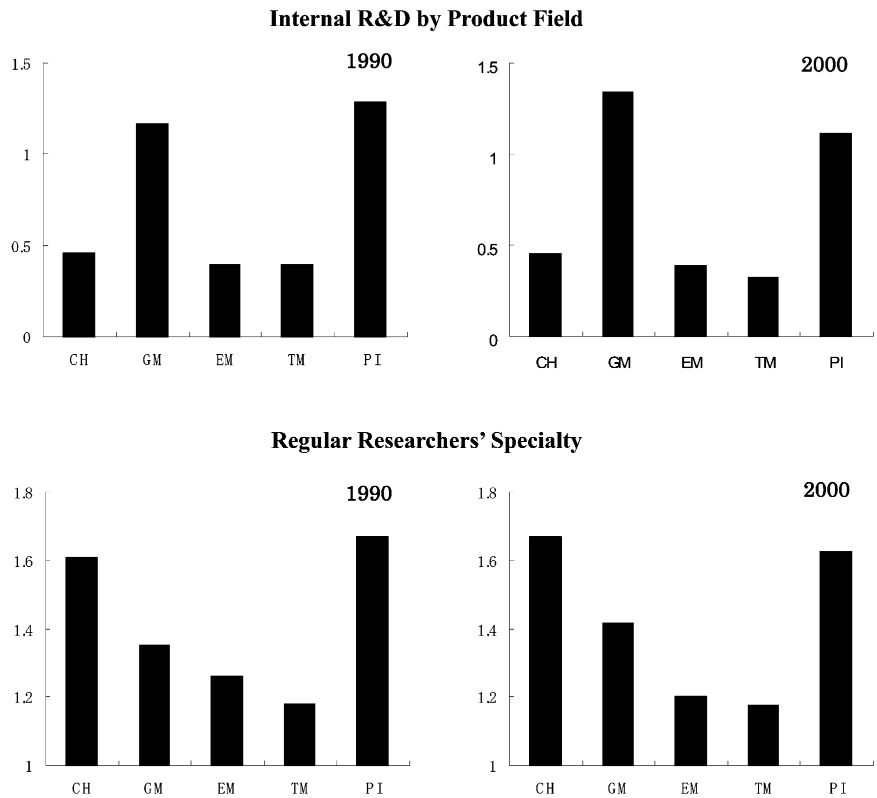


Fig. 4. Comparison of entropies of internal R&D by product field and regular researchers' specialty.

well as endogenous factors, TM's cooperative R&D structure can be identified by means of VAR.

Some pioneer works attempted to apply spectral analysis for the identification of the periodic nature of socio-economic trends. Coshall (2000) applied this to analyze international tourism flows and Berry et al. (2001) to compare the components of growth and inflation rate. However, their analyses study the trend in single entities and are insufficient for the identification of cooperative entities such as cooperative R&D.

Since Sims (1980) introduced VAR analysis into econometrics, to date, while a number of studies have applied this in macroeconomics and financial issues, few researchers have applied this to techno-economic analysis. Hsu et al. (2003) compared the performance of auto-regression (AR), VAR and Litterman Bayesian vector auto-regression (LBVAR) models to forecast the industrial production of Taiwan. Esposti (2002) conducted an empirical analysis using VAR to clarify the technological spill-in effects in the Italian national research systems. While some of these pioneer works provide constructive suggestions to the identification of interactive R&D structure, they do not necessarily elucidate a resonant cooperative R&D structure.

Stimulated by these pioneer analyses on economic resonance, this paper focuses on the empirical analysis of the smart cooperative R&D structure in Japan's TM, and attempts to elucidate its resonant cooperative R&D structure.

Section 2 provides an analytical framework with special attention to a transition from non-cooperative to cooperative R&D state. Section 3 presents results of the analyses and their implications. Section 4 briefly summarizes new findings and implications.

2. R&D cooperation and its periodicity—analytical framework

This section provides an analytical framework for the elucidation of TM's resonant cooperative R&D structure. Special attention is paid to a transition from non-cooperative to cooperative R&D state. Since sharing the same periodic nature can be considered as a basis of the resonance and such periodic nature is observed from the fluctuation of the transition, analysis of this transition is essential for the identification of resonance.

2.1. Transition from non-cooperative to cooperative R&D state: basis of the analysis

Generally, firms seek to maximize their benefits and their R&D activities are expected to make the most effective contribution to this objective. Given that cooperative R&D is beneficial to this, a firm's R&D transits to cooperative state. This is similar to the excitation of an electron to higher energy level in quantum physics. Conversely, in case the cooperative R&D loses its benefit, the firm's R&D transits to non-cooperative state. This is a reverse behavior of the above transition. Thus, the firm's cooperative R&D dynamism can be traced by these transitions. In the process of these transitions, if a firm comes across transitions of other firms with the same periodic nature, they resonate with each other, leading to extraordinary benefits from the cooperative R&D. Thus, the firm's cooperative R&D dynamism, particularly its resonant behavior, can be clearly traced in its transition process to cooperative state. This process can be classified into those with and without periodic nature. The resonance can be expected as a consequence of matching of the cycle period in the former process. Therefore, in order to identify the resonance, this matching should be analyzed by spectral analysis. The upper part of Fig. 5 illustrates this mechanism.

The impacts of the resonance on the benefits from cooperative R&D differ depending on resonating partners, and these impacts can be measured by VAR analysis. As reviewed in Section 1, the resonances can be classified into those with matured and established technology and those with emerging innovative technology. Resonance with matured established technology leads to successive assimilation resulting in decrease in the transition to cooperative state, while resonance with emerging innovative technology induces joint collaboration, accelerating the transition to cooperative state. This mechanism is illustrated in the middle part of Fig. 5.

Joint collaboration and assimilation are expected during the upswing and downswing of business cycles, respectively. Therefore, the identification of resonance types in relation with the status of business cycles is crucial for the cooperative R&D strategy of a firm. This correlation can be analyzed by means of AR and spectral analyses. The lower part of Fig. 5 illustrates this mechanism.

The mechanism leading to the construction of TM's smart resonant cooperative R&D structure can be elucidated by these three steps of analyses.

2.2. Model synthesis

2.2.1. Spectral analysis for nature of transition

Increasing rate of the number of cooperative firms in transition from non-cooperative to cooperative R&D state can be measured by the following logistic model:

$$\frac{dn_{nc\to c}}{dt} = u_c \frac{n}{N}(N-n) \tag{1}$$

where N: number of firms performing R&D; n: number of firms outsourcing R&D; $dn_{nc\to c}$: increase in the number of cooperative firms; and u_c: transition rate from non-cooperative to cooperative R&D state.

The left-hand side of Eq. (1) indicates the increasing rate of the number of cooperative firms ($dn_{nc\to c}/dt$). This is determined by the number of non-cooperative firms ($N-n$) willing to be cooperative by outsourcing R&D (n/N) multiplied by the transition rate (u_c).

Similarly, the decreasing rate of the number of cooperative firms can be measured as follows:

$$\frac{dn_{c\to nc}}{dt} = u_{nc} \frac{(N-n)}{N} n \tag{2}$$

where $dn_{c\to nc}$: decrease in the number of cooperative firms; and u_{nc}: transition rate from cooperative to non-cooperative R&D state.

Change rate of the number of firms in cooperative R&D state can be measured as a balance of Eqs. (1) and (2) as follows:

$$\frac{dn_{nc\to c}}{dt} - \frac{dn_{c\to nc}}{dt} = (u_c - u_{nc})\frac{n}{N}(N-n) \tag{3}$$

Since the left-hand side of Eq. (3) is equivalent to dn/dt, Eq. (3) can be depicted as follows:

$$\frac{dn}{dt} = u\frac{n}{N}(N-n) \tag{4}$$

where dn/dt: change rate of the number of firms in cooperative R&D state; and $(u_c - u_{nc}) \equiv u$: net transition rate from non-cooperative to cooperative R&D state.

Consequently, the change rate of the number of cooperative firms in a sector at time t can be computed as follows:

$$\frac{dn_t}{dt} = u_t \frac{n_t}{N_t}(N_t - n_t) \tag{5}$$

where N_t: number of firms performing R&D at time t; n: number of firms outsourcing R&D at time t; dn_t: change in the number of cooperative firms at time t; and u_t: net transition rate from non-cooperative to cooperative R&D state at time t.

Thus, the transition rate from non-cooperative to cooperative R&D state (hereinafter called "transition rate") u_t can be computed by the following equation:

$$u_t = \frac{dn_t}{dt} \Big/ \frac{n_t}{N_t}(N_t - n_t) \tag{6}$$

Making use of the data obtained from the Statistical Bureau of the Management and Coordination Agency over the period 1969–2000, the transition rates of the 13 sectors of the Japanese manufacturing industry are measured. The measured transition rates of the 13 sectors have fluctuated over the period examined. While the magnitudes of the rates have varied depending on sector, there is little increasing trend in the transition rate in the 13 sectors.

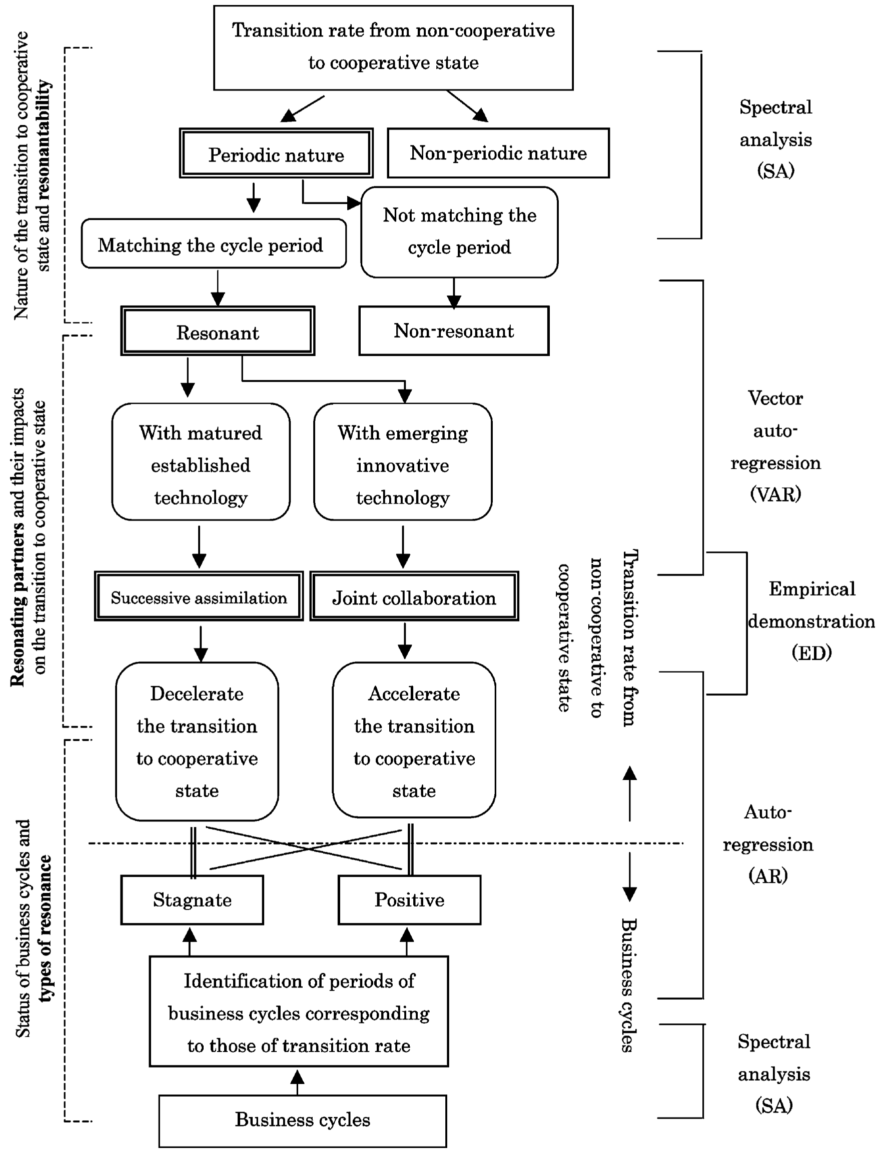


Fig. 5. Framework of the analysis of the resonant cooperative R&D structure.

Based on these transition rates, spectral analysis is attempted for the identification of the resonance. First, in order to examine whether there exists any periodic nature in the transition rate, a series of analyses are attempted by decomposing the transition rate (u_t) into constant and fluctuating terms by introducing the average transition rate ($\bar{u}$) and the fluctuating rate depending on time (u'_t) as follows:

$$u_t = \bar{u} + u'_t \tag{7}$$

where $\bar{u}$ is constant over the examined period, and $\sum u'_t = 0$.

From Eq. (7), the periodic nature of cooperative R&D structure can be analyzed by tracing the trend in the fluctuating rate (u'_t). Considering the fluctuating behavior of the fluctuating rate u'_t under $\sum u'_t = 0$ condition, the transition (u_t) in Eq. (7) can be developed by the following Fourier series equation:

$$u_t = \bar{u} + u'_t = f(t) = A_0 + \sum_{n=1}^{\infty}\left[A_n \cos\frac{2\pi nt}{T} + B_n \sin\frac{2\pi nt}{T}\right] \tag{8}$$

where $A_0 = \bar{u}$, $u'_t = \sum_{n=1}^{\infty}[A_n\cos(2\pi nt/T) + B_n\sin(2\pi nt/T)]$, $-T/2 \leq t < T/2$, and T: time period examined.

The Fourier series depicted by Eq. (8) represents the behavior of u'_t by cosine and sine functions with various periods (period for a cycle).[4] Consequently, the existence

[4] An interval of time characterized by the cycles of cosine and sine functions, measured by T/n in this case.

of the periodic nature in u_t can be identified by the power of the respective component (cosine and sine functions with respective period) P_n. P_n can be computed by spectral analysis of this Fourier series and expressed as follows by means of amplitudes of cosine and sine functions of Eq. (8), A_n and B_n, and time period examined T (see Appendix C):

$$P_n = \frac{T^2}{4}\left(A_n^2 + B_n^2\right) \tag{9}$$

As a result of spectral analysis using the fast Fourier transform, periodograms can be obtained of which the vertical and horizontal axes represent power and period (years/cycle). The peaked powers and corresponding periods are identified as meaningful components of the examined function.

2.2.2. Vector auto-regression for impacts of resonating partners

Based on the spectral analysis, in order to shed light on TM's inter-sectoral resonant cooperative R&D structure, sectors sharing the same periods as TM are selected. Since these sectors are assumed to have linked with TM by inter-sectoral R&D cooperation, the impacts of this linkage is evaluated by means of the following VAR model with exogenous and endogenous lagged variables:

$$u_{\mathrm{TM}t} = \sum_a \alpha_a u_{\mathrm{TM}t-a} + \sum_i \sum_a \beta_{ia} u_{it-a} + \mathrm{const} \tag{10}$$

where $u_{\mathrm{TM}t}$: transition rate of TM at time t; a: periods of TM identified by spectral analysis; i: sectors sharing the same periods as TM; α_a: coefficient of u_{TM} at time $t-a$; and β_{ia}: coefficient of u_i at time $t-a$.

2.2.3. Auto-regression for status of business cycles

Utilizing the periodic nature identified by spectral analysis, the relationship between the resonance type and status of business cycles is analyzed by means of the following AR model:[5]

$$y_{\mathrm{TM}t} = \sum_a \gamma_a y_{\mathrm{TM}t-a} + \mathrm{const} \tag{11}$$

where $y_{\mathrm{TM}t}$: state of TM's business cycle at time t represented by its production growth rate; a: periods of TM identified by spectral analysis; and γ_a: coefficient of y_{TM} at time $t-a$.

In order to elucidate the relationship between resonance type and business cycles, a correlation analysis is attempted utilizing the results of AR regression using Eq. (11) and VAR analysis using Eq. (10).

3. Periodicity and resonance of R&D structure—results and implications

3.1. Results of three steps of analyses

3.1.1. Results of spectral analysis—nature of the transition to cooperative state and resonability

Fig. 6 compares the results of spectral analysis of the 13 sectors of Japan's manufacturing industry over the period 1969–2000. Looking at Fig. 6, we note that cycles of shorter period have higher power than cycles of longer period. The periods with peak powers are identified as meaningful components in each sector. However, even though powers of periods shorter than 3 years are higher than those of the other periods, they

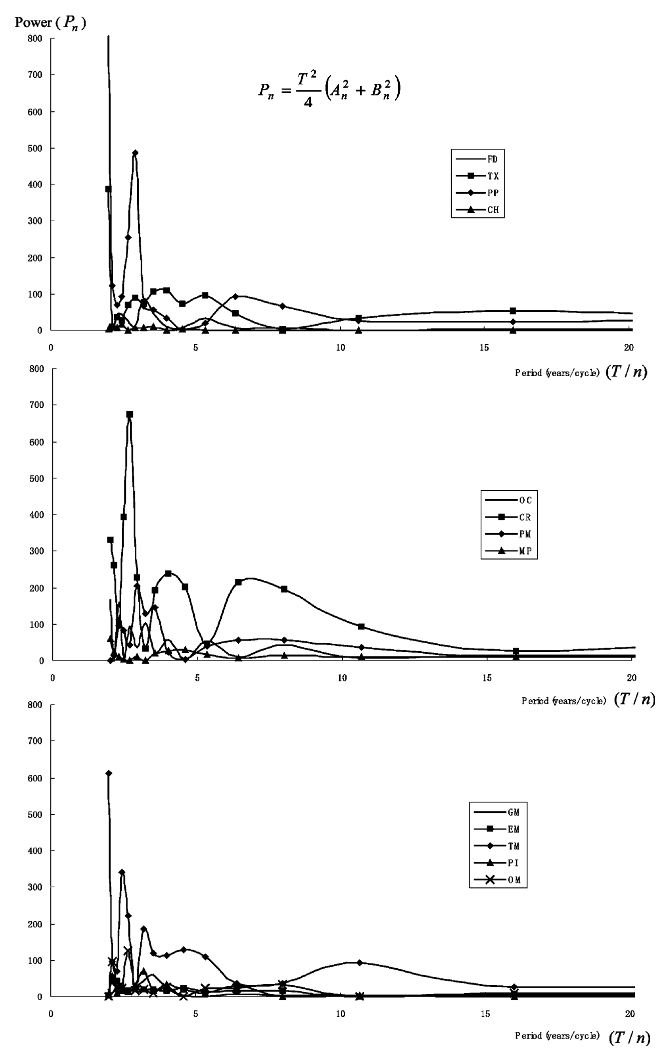


Fig. 6. Periodograms of transition rate.

[5] The spectral analysis and AR regression have been complementarily utilized as we can see from Berry et al. (2001).

Table 3
Identified periods of R&D cooperation cycles

Sector	Identified periods (years/cycle)							
FD	3		5					
TX		4	5					
PP	3			6				
CH	3		5					
OC	3		5			8		
CR		4			7			
PM	3				7			
MP	3		5			8		
GM	3				7			
EM			5		7			16
TM	*3*		*5*				*10*	
PI		4		6			10	
OM		4				8		

are considered as noise and are not taken into account because the existing literature on business cycles and innovation cycles assumes that the shortest is the 3 year cycle.[6] The periods between 3 and 16 years are identified as meaningful components of the transition rate according to the value of power. For example, although the periods with peak powers are 2, 3 and 5 years in FD, 3 and 5 year periods of cycles are identified as meaningful components of the R&D cooperation cycles. According to the periodogram obtained from spectral analysis, TM has 3, 5, and 10 year periods of cycles.

Table 3 summarizes the periods with peak powers that are regarded as meaningful R&D cooperation cycles. Although there is no common period of R&D cooperation cycles among all sectors, most of the sectors have 3 and 5 year period R&D cooperation cycles. Relatively longer 7 year periods are identified in R&D intensive sectors such as EM (16 year period), TM (10 year period) and PI (10 year period). Some sectors with not so high R&D intensity such as OC (8 year period) and OM (8 year period) have relatively longer periods.

Looking at Table 3, we note that almost all sectors except CR and OM shared certain frequencies of the same periods as TM. This is clearly observed in the R&D intensive sectors highlighted in Table 1 as follows:

CH: 3 and 5 years,
GM: 3 years,
EM: 5 years, and
PI: 10 years.

3.1.2. Results of vector auto-regression—resonating partners and their impacts on the transition to cooperative state

On the basis of the foregoing spectral analysis, taking four R&D intensive sectors (CH, GM, EM, and PI) as possible resonant partners, VAR analyses utilizing Eq. (10) are conducted based on stepwise approach. The results are summarized in Table 4.

First, taking all variables of TM and four sectors identified in Table 3 as lagged variables for endogenous and exogenous, respectively, VAR analysis is attempted. The result of the first step of regression is summarized in the upper part of Table 4.

Based on this result, the second step of regression analysis is attempted excluding statistically insignificant exogenous variables ($u_{\mathrm{CH}\,t-3}$ and $u_{\mathrm{GM}\,t-3}$, their P-values are 0.85 and 0.93, respectively). The result is summarized in the lower part of Table 4.

Looking at Table 4, we note that all variables are significant at the 10% level ($u_{\mathrm{TM}\,t-3}$, $u_{\mathrm{TM}\,t-10}$ and $u_{\mathrm{EM}\,t-5}$ are at the 5% level while TM is at the 15% level). It is also noteworthy that absolute values of coefficients of exogenous variables are larger than those of endogenous variables. This implies that the external impacts from other sectors, particularly CH, strongly influence TM's cooperative R&D structure rather than internal impacts. The values of coefficients of $u_{\mathrm{CH}\,t-5}$ and $u_{\mathrm{PI}\,t-10}$ are positive, which implies that joint collaborations are active between TM and CH as well as PI. On the contrary, the coefficient value of $u_{\mathrm{EM}\,t-5}$ is negative, which implies that TM is active in assimilating spillover technology from EM.

3.1.3. Results of auto-regression—status of business cycles and types of resonance

Utilizing Eq. (11) and applying the data on TM's gross product from Japan's national accounts (Economic Planning Agency, 1984–2000), AR analysis is conducted. The result is enumerated in Eq. (12), which demonstrates three periods of cycles (3, 5 and 10 years) in TM's business cycle:[7]

$$y_{\mathrm{TM}\,t} = \underset{(-0.47)}{-0.011} + \underset{(1.56)}{0.301} y_{\mathrm{TM}\,t-3} + \underset{(1.04)}{0.206 y_{\mathrm{TM}\,t-5}} + \underset{(2.22)}{0.493 y_{\mathrm{TM}\,t-10}} \quad \text{adj. } \underset{\mathrm{DW}=0.97}{R2 = 0.144} \qquad (12)$$

Figures in parentheses indicate t-value.

By comparing both results of VAR and AR analyses, we note that R&D activities of CH and PI resonate with that of TM corresponding to TM's business cycles while

[6] There are four major business cycles as follows:

Kitchin (or inventory) cycle (1923)	3-5 years
Juglar (or investment) cycle (1862)	7-11 years
Kuznets (or building) cycle (1930)	15-25 years
Kondratieff cycle (or long wave) (1926)	45-60 years

Source: Van Duijn (1983).

[7] Since AR analysis is to identify statistically significant periods obtained by spectral analysis, its adjusted R-squared is not necessarily a high value. For example, Berry et al. (2001) demonstrated the value of 0.28 as the coefficient of determination of their AR regression.

Table 4
Results of regression by VAR. Model: $u_{\mathrm{TM}t} = \sum_a \alpha_a u_{\mathrm{TM}t-a} + \sum_i \sum_a \beta_{ia} u_{it-a} + \mathrm{const}$

Coefficient	Sector	Variables	Estimated coefficient	Standard error	*t*-Statistic	*P*-value
First regression						
α_a	TM	$u_{\mathrm{TM}t-3}$	−0.422	0.175	−2.41	0.03
		$u_{\mathrm{TM}t-5}$	−0.115	0.143	−0.80	0.44
		$u_{\mathrm{TM}t-10}$	0.358	0.091	3.92	0.00
β_{ia}	CH	$u_{\mathrm{CH}t-3}$	0.321	0.562	0.57	0.58
		$u_{\mathrm{CH}t-5}$	1.088	0.631	1.72	0.11
	GM	$u_{\mathrm{GM}t-3}$	0.042	0.435	0.10	0.93
	EM	$u_{\mathrm{EM}t-5}$	−0.525	0.286	−1.84	0.09
	PI	$u_{\mathrm{PI}t-10}$	0.381	0.325	1.17	0.26
				Adj. R^2= 0.633; DW = 2.20		
Second regression						
α_a	TM	$u_{\mathrm{TM}t-3}$	−0.385	0.152	−2.53	0.02
		$u_{\mathrm{TM}t-5}$	−0.106	0.069	−1.53	0.15
		$u_{\mathrm{TM}t-10}$	0.365	0.081	4.49	0.00
β_{ia}	CH	$u_{\mathrm{CH}t-5}$	1.014	0.553	1.83	0.09
	EM	$u_{\mathrm{EM}t-5}$	−0.555	0.257	−2.16	0.05
	PI	$u_{\mathrm{PI}t-10}$	0.463	0.260	1.78	0.10
				Adj. R^2= 0.674; DW = 2.16		

EM's R&D resonates with TM corresponding to the reverse business cycle of TM as summarized in Table 5.

These corresponding and non-corresponding behaviors suggest that TM's cooperative R&D structure consists of joint collaboration with CH as well as PI and also assimilation effort of spillover technology from EM. While the former is accelerated during the upswing of TM's business cycles, the latter functions to supplement the decrease in TM's indigenous R&D activities due to the decline of its business cycle.

3.2. Mechanism leading to construction of TM's smart resonant cooperative R&D structure

The results of the analyses in Section 3.1 demonstrated that TM has constructed a smart cooperative R&D structure resonating with the R&D activities of partner sectors.

While TM's R&D activities entail collaboration with CH, EM and PI, TM has established a smart cooperative R&D structure by distinguishing its comparative advantage as well as development stage of technology to be introduced. TM can expect better benefits from joint collaboration with CH and PI on emerging innovative technology while it can expect benefits from assimilation of spillover technology on matured established technology from EM which has maintained comparative advantage in this technology.

Fig. 7 illustrates TM's smart cooperative R&D structure. Looking at Fig. 7, we note that while TM has assimilated electronic control units (ECU) for the advancement of fuel efficiency and low emission, it has devoted itself to joint collaboration with CH and PI on catalyst and monitor related technology for the same targets, advancement of fuel efficiency and low emission.

Fig. 8 sheds light on core technologies essential for TM's survival strategy amidst megacompetition. Advancement of fuel efficiency and low emission is crucial for TM to improve its competitiveness under

Table 5
Relationship between Resonance Type and Business Cycles

Identified period (years/cycle)	R&D cooperation partner of TM			Business cycle of TM
	CH	EM	PI	
5	+	−		+
10			+	+

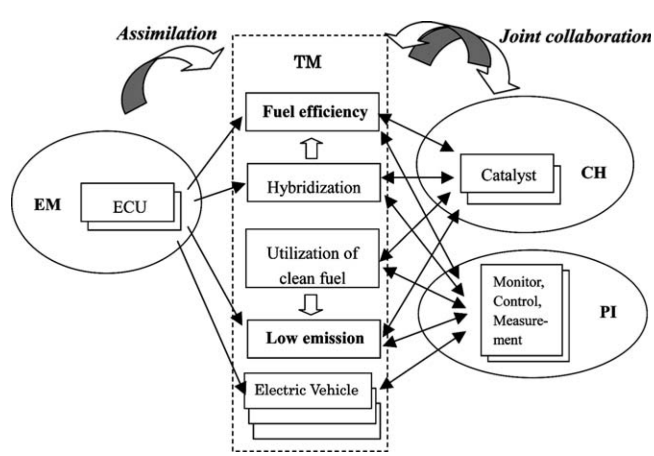
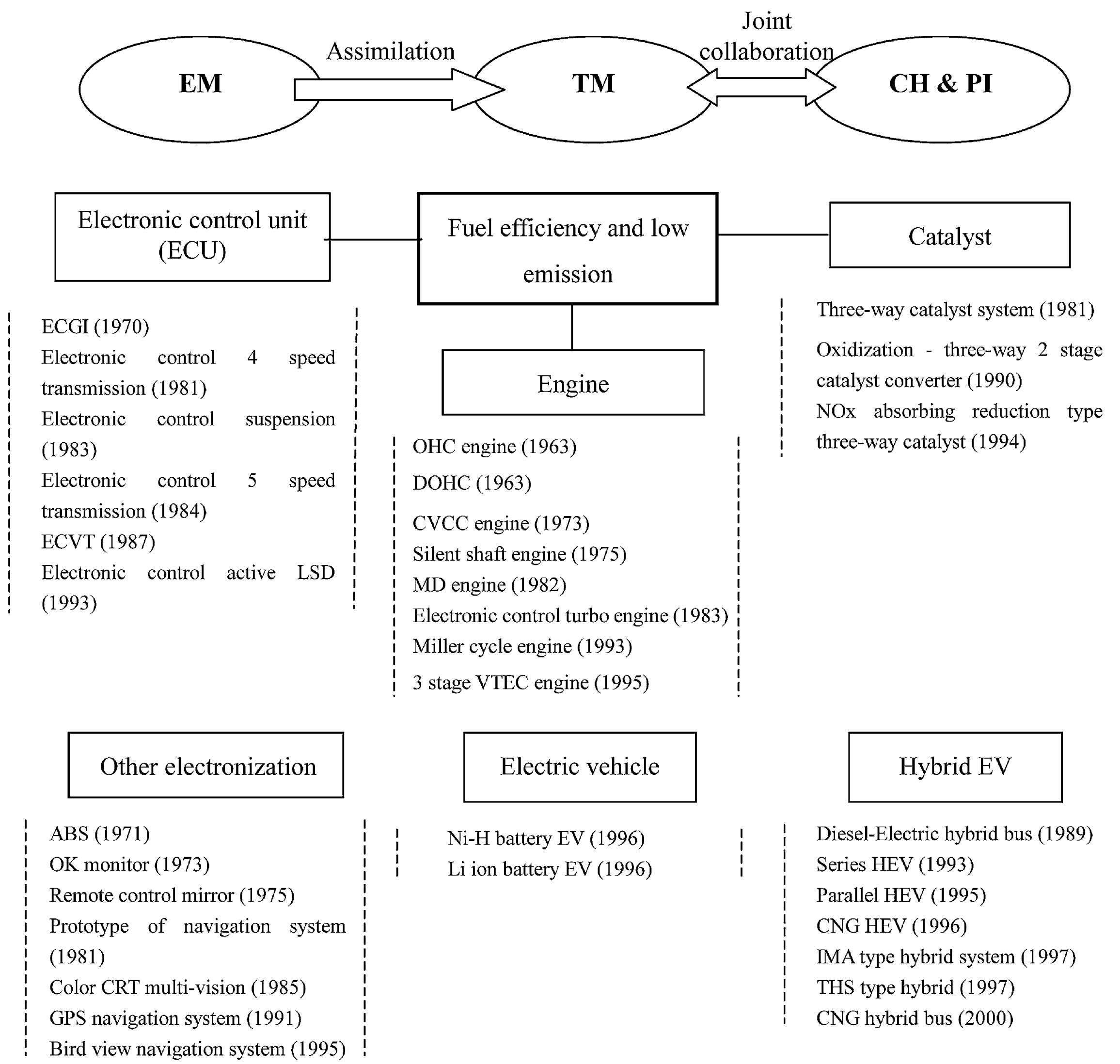


Fig. 7. TM's smart cooperative R&D structure.



Period	Institutional effort and regulation
1960s	Emission regulation (1967)
1970s - 1980s	Research Associations - Automobile equipment (1971-current) - General automobile safety and pollution (1971-current) - Automobile general control (1974-1980) - Electric car (1978-1990)
1990s	Engineering research association for super transport propulsion system (1990) ACE project[9](1997-2003) JCAP[10] (1996-2001)

[9] Advanced Clean Energy Vehicle Project.
[10] Japan Clean Air Program.

Fig. 8. Major innovations between CH, EM, PI and TM. *Source*: Arai (1995), Japan Motor Industrial Federation, Inc. (2001), Watanabe *et al.* (2002)
[a]Advanced Clean Energy Vehicle Project.
[b]Japan Clean Air Project.

increasing energy and environment constraints and subsequent stricter emission criteria.

Looking at Fig. 8, it is clearly observed that priority innovations in TM are focused on the improvement of fuel efficiency and lower emission. Major innovations in ECU and catalysts were integrated into engines and related components (Arai, 1995; Japan Motor Industrial Federation Inc., 2001).

Experiencing two energy crises, innovation efforts were focused on the improvement of fuel efficiency in the 1970s. Electronic control gasoline injection and electronic control transmission related innovations were applied. R&D consortia initiated by the Japanese government have begun to support TM for this objective (Watanabe et al., in press). These kinds of R&D consortia have promoted joint collaborations as well as assimilations of inter-sectoral technology spillover. Japan Clean Air Program (JCAP) is one of the major joint collaboration between CH and TM. The Petroleum Energy Center has led this large R&D program with financial and technical assistance from the Petroleum Association of Japan and Japan Automobile Manufacturers Association under the jurisdiction of the Ministry of International Trade and Industry (MITI) since 1996.

During the 1980s, strengthened environment regulations induced the development of emission technology. Development of the three-way catalyst system made it possible to dramatically reduce emission gases such as CO, HC and NO_x in 1981 and paved the way for further enhancement of its performance. Since it is crucial to develop $DeNO_x$ catalysts in future for compliance with more stringent environmental regulations, the joint collaboration between TM and CH as well as PI has been maintained.

Although some electronic equipment such as ABS (anti-lock braking system, 1971), OK monitor (1973) and remote control mirror (1975) were utilized for the enhancement of safety and driver-friendliness, the IT revolution has accelerated assimilation and introduction of modularized electronic equipment from EM for the enhancement of driver-friendliness which led to IT convergence after the 1980s.

4. Conclusion

In light of increasing significance of an effective cooperative R&D amidst megacompetition while facing economic stagnation, this paper focused on TM's conspicuous improvement in marginal productivity of technology by depending on smart cooperative R&D structure. This achievement can be attributed to the resonant cooperative R&D structure enabling the effective utilization of spillover technology and joint collaborative R&D.

Prompted by this postulate, this paper attempted to elucidate the mechanism enabling TM to construct the smart cooperative R&D structure by the following three step empirical analyses based on the pioneer works on economic resonance:

1. The periodic nature of 13 sectors in Japan's manufacturing industry was identified by means of spectral analysis.
2. Sectors having the same periodic nature were selected to verify the significance of their impacts on TM's cooperative R&D structure by means of VAR.
3. The relationship between resonance type and business cycles was analyzed by AR and spectral analyses.

Through these analyses, the following noteworthy findings were obtained:

1. TM maintains 3, 5 and 10 year periodic nature in its R&D cooperation and its potential R&D partners shared periodic nature as follows: CH (3 and 5 years), GM (3 years), EM (5 years) and PI (10 years).
2. The smart cooperative R&D structure of TM can be attributed to the resonance with CH, EM and PI. While TM's linkage with CH and PI accelerate R&D cooperation among them, that with EM reduces TM's R&D cooperation. It implies that TM secures its comparative advantage by integrating the joint collaborations with CH and PI on emerging innovative technologies and the assimilation of matured established spillover technologies from EM.
3. While joint collaboration with CH and PI is accelerated during the upswing of TM's business cycles, the assimilation effort of spillover technology from EM functions to supplement the decrease in TM's indigenous R&D activities due to decline of its business cycle.

Given that the effective cooperative R&D structure is a crucial survival strategy for R&D intensive industries amidst megacompetition, TM's smart cooperative R&D structure provides constructive suggestions for their survival strategies.

Further analysis should focus on the investigation of the applicability of TM's smart cooperative R&D structure to other R&D intensive manufacturing sectors. In addition, further identification of the effective inducement of R&D resonance should be developed.

Appendix A Source of data

The number of firms performing R&D is the sum of the number of firms investing in in-house R&D and that of firms outsourcing R&D minus that of firms investing in R&D in both ways.

The number of firms outsourcing R&D includes that of firms procuring R&D from the firms within and out of sector, government research institutes, universities, and foreign institutes.

The above-mentioned data are collected from Table 4 in the Report on the Survey of Research and Development by the Statistical Bureau, Management and Coordination Agency, Japan, from 1969 to 2000.

Appendix B. Productivity analysis

$V=F(X,T)$, where V is GDP; X is labor (L), capital (K); and T is technology stock

$$\frac{dV}{dt} \equiv \Delta V, \quad \frac{dX}{dt} \equiv \Delta X, \quad \frac{dT}{dt} \equiv \Delta T \approx R \quad \text{(R\&D expenditure)}$$

$$\frac{\Delta V}{V} = \sum_{X=L,K}\left(\frac{\partial V}{\partial X}\cdot\frac{X}{V}\right)\frac{\Delta X}{X} + \left(\frac{\partial V}{\partial T}\cdot\frac{T}{V}\right)\frac{\Delta T}{T} \approx \sum_{X=L,K}\left(\frac{\partial V}{\partial X}\cdot\frac{X}{V}\right)\frac{\Delta X}{X} + \frac{\partial V}{\partial T}\cdot\frac{R}{V}$$

Computation of power by Fourier transform

From Eq. (8), A_0, A_n and B_n can be expressed as follows (see note on details of mathematical development):

$$A_0 = \bar{u} = \frac{1}{T}\int_{-T/2}^{T/2} f(t)\,dt$$

$$A_n = \frac{2}{T}\int_{-T/2}^{T/2} f(t)\cos\frac{2\pi nt}{T}dt$$

$$B_n = \frac{2}{T}\int_{-T/2}^{T/2} f(t)\sin\frac{2\pi nt}{T}dt \qquad (A.1)$$

Let $A_0=(1/T)a_0$, $A_n=(2/T)a_n$ and $B_n=(2/T)b_n$, then Eq. (8) can be rewritten as follows:

$$f(t) = \frac{a_0}{T} + \frac{2}{T}\sum_{n=1}^{\infty}\left[a_n\cos\frac{2\pi nt}{T} + b_n\sin\frac{2\pi nt}{T}\right] \qquad (A.2)$$

Using the definition of cosine and sine in terms of exponential functions,

$$\cos\theta = \frac{1}{2}\left(e^{j\theta}+e^{-j\theta}\right), \quad \sin\theta = \frac{1}{2j}\left(e^{j\theta}-e^{-j\theta}\right)$$

where e is the base of the natural logarithm and j is the imaginary unit of the complex number system $j=\sqrt{-1}$.

Eq. (A.2) can be depicted as a series of exponential functions as follows:

$$f(t) = \frac{a_0}{T} + \frac{2}{T}\sum_{n=1}^{\infty}\frac{1}{2}\left[(a_n - jb_n)\exp\left(j\frac{2\pi nt}{T}\right) + (a_n + jb_n)\exp\left(-j\frac{2\pi nt}{T}\right)\right] \qquad (A.3)$$

Let $X_0=a_0$, $X_n=(a_n-jb_n)$, $X_{-n}=(a_n+jb_n)$ where X_n is a complex number composed of the amplitudes of cosine and sine represented by real and imaginary terms, respectively. Thus, $f(t)$ can be depicted by a general form as follows:

$$f(t) = \frac{1}{T}\sum_{-\infty}^{\infty}X_n\exp\left(j\frac{2\pi nt}{T}\right) \qquad (A.4)$$

Conversely, X_n is expressed as follows:

$$X_n = \int_{-T/2}^{T/2} f(t)\exp\left(-j\frac{2\pi nt}{T}\right)dt \qquad (A.5)$$

[8]Therefore, X_n can be calculated by the Fourier transform of function $f(t)$.

The transition rate from non-cooperative to cooperative state u_t $(=f(t))$ consists of the constant term $(\bar{u})$ and the fluctuating term (u'_t). The periodic nature of the transition rate can be traced from u'_t composed of cosine and sine functions amounting to n, respectively. Each respective cosine and sine function has T/n period with amplitudes of A_n $(=(2/T)a_n)$ and B_n $(=(2/T)b_n)$, respectively. These functions with T/n period contain respective power (P_n) which, in Eq. (A.3), developed from the Fourier series equation (A.2), is equivalent to the sum of the square of real value (a_n) and imaginary value (b_n) as follows:

$$P_n = a_n^2 + b_n^2 \qquad (A.6)$$

From Eq. (A.5), this power can be computed simply by the product of X_n and X_{-n}. Thus, the power of respective components (cosine and sine functions with T/n period) can be measured by the following equation:

$$P_n = a_n^2 + b_n^2 = X_n X_{-n} \qquad (A.7)$$

Since $a_n=(T/2)A_n$, $b_n=(T/2)B_n$, this power can be expressed by A_n, B_n and T as follows:

$$P_n = \frac{T^2}{4}\left(A_n^2 + B_n^2\right) \qquad (A.8)$$

[8] Since

$$\int_{-T/2}^{T/2}\exp\left(j2\pi\frac{m}{T}t\right)\exp\left(-j2\pi\frac{n}{T}t\right)dt = \begin{cases} 0 & n \neq m \\ T & n = m \end{cases},$$

multiplying by $\exp(-j2\pi(n/T)t)$ on both sides of Eq. (A.4) and integrating from $-T/2$ to $T/2$, we obtain

$$\int_{-T/2}^{T/2} f(t)\exp\left(-j\frac{2\pi nt}{T}\right)dt = \frac{1}{T}(TX_n) = X_n.$$

Note: amplitudes of cosine and sine functions

The amplitudes of cosine and sine functions A_n and B_n in Eq. (8) can be developed as follows

$$\int_{-T/2}^{T/2} f(t)\cos\frac{2\pi nt}{T}\,dt = A_0\int_{-T/2}^{T/2}\cos\frac{2\pi nt}{T}\,dt + A_1\int_{-T/2}^{T/2}\cos\frac{2\pi t}{T}\cos\frac{2\pi nt}{T}\,dt + \cdots + A_n\int_{-T/2}^{T/2}\cos\frac{2\pi nt}{T}\cos\frac{2\pi nt}{T}\,dt + \cdots + B_1\int_{-T/2}^{T/2}\sin\frac{2\pi t}{T}\cos\frac{2\pi nt}{T}\,dt + \cdots + B_n\int_{-T/2}^{T/2}\sin\frac{2\pi nt}{T}\cos\frac{2\pi nt}{T}\,dt + \cdots$$

where

$$\int_{-T/2}^{T/2}\cos\frac{2\pi nt}{T}\,dt = \begin{cases} 0 & n \neq 0 \\ T & n = 0 \end{cases}$$

$$\int_{-T/2}^{T/2}\cos\frac{2\pi mt}{T}\cos\frac{2\pi nt}{T}\,dt = \begin{cases} 0 & n \neq m \\ T/2 & n = m \neq 0 \end{cases}$$

$$\int_{-T/2}^{T/2}\sin\frac{2\pi mt}{T}\cos\frac{2\pi nt}{T}\,dt = 0$$

As a result,

$$\int_{-T/2}^{T/2} f(t)\cos\frac{2\pi nt}{T}\,dt = A_n\frac{T}{2}$$

Therefore,

$$A_n = \frac{2}{T}\int_{-T/2}^{T/2} f(t)\cos\frac{2\pi nt}{T}\,dt$$

Similarly, B_n can be obtained as follows:

$$\int_{-T/2}^{T/2} f(t)\sin\frac{2\pi nt}{T}\,dt = A_0\int_{-T/2}^{T/2}\sin\frac{2\pi nt}{T}\,dt + A_1\int_{-T/2}^{T/2}\cos\frac{2\pi t}{T}\sin\frac{2\pi nt}{T}\,dt + \cdots + A_n\int_{-T/2}^{T/2}\cos\frac{2\pi nt}{T}\sin\frac{2\pi nt}{T}\,dt + \cdots + B_1\int_{-T/2}^{T/2}\sin\frac{2\pi t}{T}\sin\frac{2\pi nt}{T}\,dt + \cdots + B_n\int_{-T/2}^{T/2}\sin\frac{2\pi nt}{T}\sin\frac{2\pi nt}{T}\,dt + \cdots$$

where

$$\int_{-T/2}^{T/2}\sin\frac{2\pi nt}{T}\,dt = 0$$

$$\int_{-T/2}^{T/2}\cos\frac{2\pi mt}{T}\sin\frac{2\pi nt}{T}\,dt = 0$$

$$\int_{-T/2}^{T/2}\sin\frac{2\pi mt}{T}\sin\frac{2\pi nt}{T}\,dt = \begin{cases} 0 & n \neq m \\ T/2 & n = m \neq 0 \end{cases}$$

As a result,

$$\int_{-T/2}^{T/2} f(t)\sin\frac{2\pi nt}{T}\,dt = B_n\frac{T}{2}$$

Therefore,

$$B_n = \frac{2}{T}\int_{-T/2}^{T/2} f(t)\sin\frac{2\pi nt}{T}\,dt$$

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