A Highly Efficient P-SSHI Rectifier for Piezoelectric Energy Harvesting

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Abstract—A highly efficient P-SSHI based rectifier for piezoelectric energy harvesting is presented in this paper. The proposed rectifier utilizes the voltages at the two ends of the piezoelectric device (PD) to detect the polarity change of the current produced by the PD. The inversion process of the voltage across the PD is automatically controlled by diodes along the oscillating network. In contrast to prior works, the proposed rectifier exhibits several advantages in terms of efficiency, circuit simplicity, compatibility with commercially available PDs, and standalone operation. Experimental results show that the proposed rectifier can provide a 5.8X boost in harvested energy compared to the conventional full wave bridge rectifier.

Index Terms—Piezoelectric energy harvesting, Parallel Synchronized Switch Harvesting on Inductor, AC-DC converter.

I. INTRODUCTION

Harvesting ambient vibration energy provides a means to extend battery operation and enable self-powered ultra-low power devices, such as wireless human body health monitoring sensors or medical implants (e.g. implantable heart assists) [1-3]. A piezoelectric device (PD) (Fig. 1) vibrating at or close to its resonant frequency can be modeled as a sinusoidal current source i_p in parallel with its internal capacitance C_p and resistance R_p [3]. The ac signal produced by the PD needs to be rectified for most applications. Given that the amplitude of the current i_p generated by the PD is low (within micro-amp range) [4], the efficiency of the rectification must be as high as possible.

Fig. 1 Equivalent circuit of a PD vibrating around its resonant frequency

Conventional ac to dc rectification circuits for PDs include the full wave bridge rectifier (Fig. 2(a)) and the voltage doubler (Fig. 2(b)). Such circuits suffer from low efficiency due to the internal capacitance of the PD [4]. For the full wave bridge rectifier (Fig. 2(a)), the output current i_p of the PD needs to charge (and discharge) the internal capacitance C_p from

$-(V_{\text{rect}} + 2V_D)$ to $V_{\text{rect}} + 2V_D$ (or vice versa), before the current i_p can actually flow to the output. This occurs every half cycle for the full wave bridge rectifier. In the case of the voltage doubler (Fig. 2(b)), the current i_p cannot flow to the output every half cycle. This is because diode D6 is turned ON during the negative half cycle, with current i_p flowing to ground. The shaded areas in Fig. 2 represent non-harvesting periods.

Fig. 2 (a) Full wave bridge rectifier and associated waveforms, (b) voltage doubler and associated waveforms

The PD's internal capacitance can be exploited to realize energy conversion input resonant circuits working synchronously with the vibration [5]. A well-known technique based on this approach is the Synchronized Switch Harvesting on Inductor (SSHI) technique proposed in [6]. In this technique, the PD is connected in parallel with a switch and an inductor. This technique is also called parallel SSHI (P-SSHI) (Fig. 3(a)). It operates as follows (Fig. 3(b)). At the beginning of every half cycle, the current i_p produced by the PD changes polarity and the switch M1 is closed. As a result, the inductor L and internal capacitance C_p of the PD forms an oscillating network and the voltage across the PD is naturally inverted. This occurs without the energy generated by the PD being used to charge/discharge the internal capacitance C_p . A similar technique called series-SSHI (S-SSHI) (Fig. 4(a)) was proposed in [7]. Instead of connecting the switch and inductor in parallel with the PD, the switched inductor is connected in series with the PD. The

switch control strategy (Fig. 4(b)) is identical to that of the P-SSHI technique. When the current i_p changes polarity, the switch M2 is closed and the energy stored in C_p is transferred to the output capacitor C_{rect} and the voltage across the PD is inverted through the rectifier bridge. The switch M2 is opened at the end of the inversion process, after which M2 remains opened until the next half cycle. The analysis presented in [8] shows that the performance of P-SSHI is better than that of S-SSHI, especially when the open-circuit voltage of the PD is low. To realize the P-SSHI or S-SSHI technique, there are four main implementation challenges associated to circuit complexity, compatibility with commercially available PDs, standalone operation and harvested energy. These are: (1) detecting automatically the polarity change of the current produced by the PD. This should occur every half cycle, with a frequency of vibrations typically lower than 300Hz; (2) controlling automatically the switch ON time to match the duration of the inversion process. The switch ON time, which is of the order of microseconds, should allow for the internal capacitance C_p to fully discharge into the inductor, but no longer to avoid C_p taking back energy from the inductor. In addition, given that the characteristics (e.g. C_p) of the PD may not be known, the switch ON time should not be preset to allow compatibility of the rectifier with different types of PD; (3) the resistance of the oscillating network should be kept at a minimum to help improve the inversion process of the voltage across the PD; and (4) keeping the total power consumption of all circuits lower than the harvested energy to ensure self-powered operation.

Fig. 3 (a) P-SSHI technique and (b) associated waveforms, (c) and (d) implementations of P-SSHI

[4] proposed an implementation (Fig. 3(c)) of the P-SSHI technique, where switch M1 is implemented using two transistors. In this implementation, switch M1's ON time is controlled by a digital inverter delay line. The latter is constructed using inverter chains including multiplexers. By applying different control words to the multiplexers, the delay line can be programmed to achieve different values of the ON time. However, the control words need to be generated externally and tuned to accommodate the internal capacitance of each specific PD. Another implementation (Fig. 3(d)) of the P-SSHI technique was presented in [5]. The rectifier uses two

transistors (T3 and T4) and two diodes for switch M1. When the current i_p changes polarity, the voltage signal generated by the passive differentiator changes polarity at the same time. The comparator's output turns on transistors T3 and T4 at the beginning of every half cycle. In this implementation, the comparator needs both positive and negative voltage supplies. In [9, 10], we proposed to use comparators and logic circuits to control the switch ON time while alleviating the need for diodes along the switching path. Given that the switch ON time is of the order of several microseconds, the rectifiers in [9, 10] require circuits with very fast rise/fall times and thus relatively high energy consumption compared to the harvested energy. As a result, self-power operation was thus not achieved in [9, 10].

Fig. 4 (a) S-SSHI technique and (b) associated waveforms, (c), (d) and (e) implementations of S-SSHI

[9] proposed an implementation (Fig. 4(c)) of the S-SSHI technique. In this implementation, a displacement sensor and a processor are used for the synchronization and the generation of the switching commands. All of which need external power to run. [10, 11] implemented a self-powered S-SSHI (SP-S-SSHI) rectifier (Fig. 4(d)), which uses peak detectors to control the start of the switching time for the switch M2. However, there is always a phase lag between the peak voltage and the actual switching time. This is due to the voltage drops of diodes and transistors in the peak detector. Furthermore, this phase lag is larger for small vibrations than for large vibrations [12]. In order to eliminate the phase lag, the authors [12] designed a velocity control SSHI rectifier (Fig. 4(e)). This rectifier requires three PDs to vibrate synchronously. The first PD is used to provide power for the control circuit. The second PD is connected to a low pass filter that generates a signal to detect the polarity change of current i_p . The third PD is used for energy harvesting. This strategy results in a more complex and costly energy harvesting system. To address the above mentioned

limitations, this paper presents a simple yet highly efficient P-SSHI based rectifier. The proposed rectifier neither relies on displacement sensor, peak detectors, differentiator or filters to detect the polarity change of the current produced by the PD, nor does it rely on a DSP or processor to generate the required signals for the control of the ON time of the switch. Furthermore, the proposed rectifier only uses the harvested energy to power the control circuits, thereby alleviating the need for any additional power supply circuits. This paper is organized as follows. Section II describes the operation of the proposed rectifier and analyses the harvested and lost energy. Section III presents the experimental setup and results. A performance comparison between the proposed rectifier and reported implementations of the SSHI technique is discussed. Section IV concludes the paper.

II. PROPOSED RECTIFIER

The proposed rectifier is shown in Fig. 5(a). The voltages V_p and V_n at the two ends of the PD are used to detect the polarity change of i_p . Before time t_0 , i_p is positive, V_p is close to $(V_{rect} + V_D)$ and V_n is close to but lower than $-V_D$, where V_D is the diode's forward voltage. These two voltages are compared with V_{ref} , which is chosen slightly higher than $-V_D$. This is achieved using comparators CMP1 and CMP2. Since V_p and V_n are initially higher and lower than V_{ref} respectively, OUT_1 and OUT_2 are low and high accordingly. At this time, the output of the NOR gate N_{out} is low. When i_p changes polarity from positive to negative at time t_{0+} , V_n increases and reaches the value of V_{ref} . As a result, signal OUT_2 changes from high to low while V_p is still higher than V_{ref} and OUT_1 stays low. Therefore, N_{out} changes from low to high. This latter change is used to detect the polarity change of i_p . When i_p changes polarity again from negative to positive at time $t_{\pi+}$, a similar process occurs. Subsequently, signal N_{out} is processed to generate switching commands for transistors M1-M4. When i_p changes polarity from positive to negative at time t_{0+} , the signals ϕ_1 and ϕ_{1inv} are firstly generated. As a consequence, transistors M1 and M3 are turned ON and the oscillating network C_p -L-D5-(M1, M3) is formed. Therefore, the voltage V_f across PD is naturally inverted and this inverting process spans from t_0 to t_1 . Control signals ϕ_1 and ϕ_{1inv} are still high when the inverting process finishes, but diode D5 prevents the current flowing back, thereby terminating the inverting process. Subsequently, the current i_p charges C_p from $V_{f,invert}$ to $-(V_{rect} + 2V_D)$ during time interval $[t_1, t_2]$ and then delivers power to the output. At time $t_{\pi+}$, when i_p changes polarity again, a similar process occurs for oscillating network C_p -(M2, M4)-D6-L. Fig. 6 shows the schematic of the clock divider, whose input is N_{out} and outputs are ϕ_1 , ϕ_{1inv} , ϕ_2 and ϕ_{2inv} . Input signal N_{out} is a sequence of pulses, toggling from low to high at the beginning of every half cycle. A Divide-by-2 circuit is used to generate two groups of control signals for the two oscillating networks. This circuit is constructed using a D flip-flop with its complementary output connected to its D input and signal N_{out} fed into the CLK input. Therefore, outputs Q and Q bar both have a frequency that is half that of signal N_{out} . D flip-flop's output Q and Q bar are

ANDed with a delayed version of signal N_{out} . As a result, signals ϕ_1 and ϕ_2 have the same pulse width than signal N_{out} but half its frequency. ϕ_{1inv} and ϕ_{2inv} are the inverted versions of ϕ_1 and ϕ_2 .

Fig. 5 (a) Implementation of the proposed rectifier and (b) associated current and voltage waveforms

Fig. 6 Clock divider

As it can be seen from Fig. 4(b), the PD charges its internal capacitance C_p from $V_{f,invert}$ to $(V_{rect} + 2V_D)$ or $-V_{f,invert}$ to

$-(V_{rect}+2V_D)$. Therefore, the charge lost on C_p in the time interval $[t_1, t_2]$ is:

$$Q_{Cp,loss} = (V_{rect} + 2V_D - V_{f,invert})C_p \quad (1)$$

where $V_{f,invert}$ is the inverted voltage V_f at the beginning of every half cycle and is given by

$$V_{f,invert} = (V_{rect} + 2V_D)e^{-\frac{\pi}{Q}} - V_D \left(1 + e^{-\frac{\pi}{Q}}\right) \quad (2)$$

Q is the quality factor of the oscillating network and is given by:

$$Q = \frac{\omega}{\alpha} \quad (3)$$

where $\omega = \sqrt{\omega_o^2 - \alpha^2}$, $\omega_o = \frac{1}{\sqrt{LC_p}}$ and $\alpha = \frac{R_{para}}{2L}$, R_{para} is the parasitic resistance of the oscillating network.

Hence the charge lost on the C_p every half cycle is:

$$Q_{Cp,loss} = (V_{rect} + 2V_D) \left(1 - e^{-\frac{\pi}{Q}}\right) C_p + V_D \left(1 + e^{-\frac{\pi}{Q}}\right) C_p \quad (4)$$

The charge lost on the internal resistance R_p every half cycle is

$$Q_{Rp,loss} = \int_{t_0}^{t_1} \frac{V_f}{R_p} dt \quad (5)$$

In time interval $[t_0, t_1]$, V_f is inverted by the oscillating network and the length of this time interval is given by

$$t_1 - t_0 = \pi \sqrt{LC_p} \quad (6)$$

Since the time interval $[t_0, t_1]$ is very short compared to the half cycle of current i_p , the energy lost in this time interval can be neglected. Then, in time interval $[t_1, t_2]$, the charge lost on R_p is:

$$Q_{Rp,loss1} = \int_{t_1}^{t_2} \frac{V_{f,t_1-t_2}}{R_p} dt \quad (7)$$

and in this time interval, V_f is given by:

$$\begin{aligned} V_{f,t_1-t_2} &= \frac{1}{C_p} \int_{t_1}^t I_p \sin \omega t dt + V_f(t_1) \\ &= \frac{I_p}{\omega C_p} (\cos \omega t_1 - \cos \omega t) + V_f(t_1) \end{aligned} \quad (8)$$

The boundary condition for V_f is $V_f(t_1) = (V_{rect} + 2V_D)e^{-\frac{\pi}{Q}}$ and $\omega t_1 \approx 0$. V_p is the open circuit voltage of PD, defined as

$$V_p = \frac{I_p}{\omega C_p} \quad (9)$$

hence,

$$V_{f,t_1-t_2} = V_p(1 - \cos \omega t) + (V_{rect} + 2V_D)e^{-\frac{\pi}{Q}} \quad (10)$$

Bringing (10) back to (7), we obtain:

$$\begin{aligned} Q_{Rp,loss1} &= \int_{t_1}^{t_2} \frac{V_{f,t_1-t_2}}{R_p} dt \\ &= \frac{V_p(\omega t_2 - \sin \omega t_2)}{\omega R_p} + \frac{(V_{rect} + 2V_D)e^{-\frac{\pi}{Q}}}{R_p} \end{aligned} \quad (11)$$

where

$$\omega t_2 = \cos^{-1} \left(1 - \frac{(V_{rect} + 2V_D) \left(1 - e^{-\frac{\pi}{Q}}\right)}{V_p} \right) \quad (12)$$

In time interval $[t_2, t_\pi]$, the charge lost on R_p is

$$Q_{Rp,loss2} = \frac{V_{rect} + 2V_D}{R_p} (t_\pi - t_2) \quad (13)$$

where

$$t_\pi = \frac{\pi}{\omega} \quad (14)$$

The total charge produced by PD in every half cycle is:

$$Q_{total} = 2C_p V_p = \frac{2I_p}{\omega} \quad (15)$$

Therefore, the harvested power for every cycle is

$$P_{harvest} = 2f_p V_{rect} (Q_{total} - Q_{Cp,loss} - Q_{Rp,loss1} - Q_{Rp,loss2}) \quad (16)$$

III. EXPERIMENTAL RESULTS AND DISCUSSION

The performance of the proposed rectifier was evaluated (Fig. 7) using a commercially available PD of dimensions $1.4 \times 0.24 \times 0.025$ (inch) (V22B Mide Technology) mounted on a shaker (Labworks ET-126-B1). The shaker was excited at 225 Hz and driven by a sine wave generator (Labworks SG-135) amplified through a power amplifier (Labworks PA-138). The proposed rectifier was built using ultra-low power off-the-shelf ICs. Comparators CMP1 and CMP2 (Fig. 4(a)) were implemented using two ultra-low power ICs (LTC1540, Linear Technology, 680 nA max quiescent supply current). The NOR gate and the clock divider (Fig. 5) were implemented using Standard CD-4000 Series CMOS gates with low input current leakage. Switches along the oscillating networks were implemented using two types of MOSFETs (VN0104 and VP0104), with on resistance of 3Ω and 11Ω for a gate voltage of 5V, respectively. The diodes in the oscillating networks are Schottky diodes (BAT54) with a forward voltage of 0.2 V.

Fig. 8 shows the measured voltage waveforms across the PD and the output voltage V_{rect} for the proposed rectifier and full wave bridge rectifier. The measured waveforms are consistent with the operation waveforms shown in Fig. 5(b). As seen in Fig. 8(a), the inversion process occurs each time V_p or V_n reaches V_{ref} . The control circuit can thus automatically detect the starting time of the inversion process. Note that the inversion process is not perfect with $V_{f,invert}$ lower than V_f

Fig. 7 Experimental Setup

(a)

(b)

Fig. 8 Measured waveforms of voltage across the PD and output voltage V_{rect} for (a) the proposed rectifier and (b) full wave bridge rectifier

because of the parasitic resistance (from inductor L and switches) along the oscillating network. In Fig. 8(a), the current i_p generated by the PD only needs to charge the internal capacitance C_p from the inverted voltage $V_{f,invert}$ to the $\pm(V_{rect} + 2V_D)$, before charges can flow to the output. A significant amount of charges have thus been saved. This can be seen by comparing the amplitudes of the voltage V_f in Fig. 8(a) and Fig. 8(b). With a $114.1 \text{ k}\Omega$ resistance attached to the output, the output voltage of the proposed rectifier can reach up to 2 V . In contrast, the full wave bridge rectifier could only provide an output voltage of 0.823 V . Fig. 9 shows the measured output power of the proposed rectifier (with different values of inductors) together with that of the full wave bridge rectifier as a function of the output voltage. The open-circuit voltage V_p of the PD was set to 2.4 V . The curve at the bottom of Fig. 8 with triangle symbols shows that the full wave bridge rectifier's maximum harvested power is $8.28 \text{ }\mu\text{W}$ for an output voltage of 0.6 V . The middle curve with star symbols shows that the

proposed rectifier (with a $22 \text{ }\mu\text{H}$ inductor) can provide a maximum harvested power of $20 \text{ }\mu\text{W}$ for an output voltage of 1.6 V . This maximum output power is $2.45\times$ that of the full wave bridge rectifier. The top curve with square symbols is the output power of the proposed rectifier with a $940 \text{ }\mu\text{H}$ inductor. This curve shows that the maximum harvested power of the proposed rectifier is $48 \text{ }\mu\text{W}$ for an output voltage of 2.6 V . This value is $5.8\times$ that of the full wave bridge rectifier.

Fig. 9 Output power vs output voltage for the proposed rectifier and the full wave bridge rectifier

Fig. 10 Output power of externally powered and self-powered rectifiers, with power consumption of control circuits

Fig. 10 reports the output power of implemented externally powered and self-powered (by output voltage V_{rect}) rectifiers together with the power consumption of control circuits. The open-circuit voltage V_p of the PD was set to 3.28 V . The output power of the self-powered rectifier is lower than that of the externally powered rectifier. The difference in the output power is the total power consumption of control circuits (blue bars in Fig. 10). When the output voltage V_{rect} is less than 1.8 V , the control circuits are inactive, since this voltage is less than the minimum positive voltage supply requirement for the comparators. Table I compares the performance of the proposed rectifier against state-of-the-art SSHI implementations for piezoelectric energy harvesting. The

second line of Table I

TABLE I – PERFORMANCE COMPARISON WITH REPORTED SSHI RECTIFIERS

Publication	[4]	[5]	[10]	[12]	This Work
Type of Implementation	Integrated	Discrete	Discrete	Discrete	Discrete
Max Quiescent Current of Control Circuits	>220 nA	4000 nA	Not shown	>800 nA	4900 nA
Piezoelectric Device (PD)	V22B Mide Technology	RBL1-006 Piezo System	T120-A4E-602 Piezo System	Custom Design	V22B Mide Technology
Amplitude I_p of Current produced by PD	63 μ A	1.4 mA	157.72 μ A	88 μ A	63 μ A
Internal Capacitance C_p	18 nF	60 nF	33.47 nF	25 nF	18 nF
Vibration Frequency	225 Hz	185 Hz	30 Hz	12.5 Hz	225 Hz
Performance compared with a Full Wave Bridge Rectifier	4X	2.3X	2X	2X	5.8X

outlines the type of implementation. Only [4] reports a CMOS integration. The advantage of such an implementation is that the quiescent current can be tailored to provide the lowest power consumption for the control circuits. All works listed in Table I rely on commercially available PDs to test the performance of the rectifiers, except [12]. The latter requires 3 PDs for the rectifier implementation, with all 3 PDs needing to vibrate synchronously. This requirement increases the complexity and cost of the whole energy harvesting system. Line 5 of Table I reports the amplitude I_p of the current produced by the PD for each prior work. This amplitude depends on several factors such as the piezo material properties, vibration acceleration, PD dimensions, to name a few. Usually a PD producing a higher amplitude I_p would generate more energy, as seen from (15). However, a higher I_p does not necessarily translate into more harvested energy as the internal capacitance C_p is a major source of power loss for the rectifier. A larger C_p implies more energy loss for every half cycle of i_p , as seen from (1). This makes direct comparison with other works difficult. However, taking the conventional full wave bridge rectifier as a common reference, the proposed rectifier can improve the harvested energy by up to 5.8X compared to the conventional full wave bridge rectifier.

IV. CONCLUSION

A simple yet highly efficient rectifier is proposed for piezoelectric energy harvesting. The proposed P-SSHI rectifier does not require any external signals to detect the polarity change of the current produced by the piezoelectric device (PD). Rather, it uses two comparators to monitor the voltages at the two ends of the PD to detect the polarity change of the current produced by the PD. Diodes along the oscillating network are used to terminate the inversion process. The proposed self-powered rectifier provides a significant 5.8X boost in terms of the harvested energy compared to the conventional full wave bridge rectifier.

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REFERENCES

- [1] N. Kong and D. S. Ha, "Low-Power Design of a Self-powered Piezoelectric Energy Harvesting System With Maximum Power Point Tracking," *IEEE Transactions on Power Electronics*, vol. 27, no. 5, pp. 2298-2308, 2012.
- [2] G. K. Ottman, H. F. Hofmann, and G. A. Lesieutre, "Optimized piezoelectric energy harvesting circuit using step-down converter in discontinuous conduction mode," *IEEE Transactions on Power Electronics*, vol. 18, no. 2, pp. 696-703, Mar 2003.
- [3] G. K. Ottman, H. F. Hofmann, A. C. Bhatt, and G. A. Lesieutre, "Adaptive piezoelectric energy harvesting circuit for wireless remote power supply," *IEEE Transactions on Power Electronics*, vol. 17, no. 5, pp. 669-676, Sep 2002.
- [4] Y. Ramadass and A. Chandrakasan, "An efficient piezoelectric energy harvesting interface circuit using a bias-flip rectifier and shared inductor," *IEEE Journal Solid-State Circuits*, vol. 45, no. 1, pp. 189-204, January 2010.
- [5] N. Kriheli and S. Ben-Yaakov, "Self-Contained Resonant Rectifier for Piezoelectric Sources Under Variable Mechanical Excitation," *IEEE Transactions on Power Electronics*, vol. 26, no. 2, pp. 612-621, Feb 2011.
- [6] D. Guyomar, A. Badel, E. Lefeuvre, and C. Richard, "Toward energy harvesting using active materials and conversion improvement by nonlinear processing," *IEEE Transactions Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 52, no. 4, pp. 584-595, 2005.
- [7] E. Lefeuvre, A. Badel, A. Benayad, L. Lebrun, C. Richard, and D. Guyomar, "A comparison between several approaches of piezoelectric energy harvesting," *Journal De Physique Iv*, vol. 128, no. pp. 177-186, Sep 2005.
- [8] J. Dicken, P. D. Mitcheson, I. Stoianov, and E. M. Yeatman, "Power-Extraction Circuits for Piezoelectric Energy Harvesters in Miniature and Low-Power Applications," *IEEE Transactions Power Electronics*, vol. 27, no. 11, pp. 4514-4529, 2012.
- [9] K. Makiyama, J. Onoda, and T. Miyakawa, "Low energy dissipation electric circuit for energy harvesting," *Smart Materials and Structures*, vol. 15, no. 5, pp. 1493-1498, October 2006.
- [10] J. R. Liang and W. H. Liao, "Improved Design and Analysis of Self-Powered Synchronized Switch Interface Circuit for Piezoelectric Energy Harvesting Systems," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 4, pp. 1950-1960, Apr 2012.
- [11] M. Lallart and D. Guyomar, "An optimized self-powered switching circuit for non-linear energy harvesting with low voltage output," *Smart Materials & Structures*, vol. 17, no. 3, pp. 30-35, Jun 2008.
- [12] C. Yu-Yin, D. Vasic, F. Costa, W. Wen-Jong, and C. K. Lee, "Self-powered piezoelectric energy harvesting device using velocity

control synchronized switching technique," in *IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society*, 2010, pp. 1785-1790.