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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 :
G06F 17/50

A1

(11) International Publication Number: WO 95/08155

(43) International Publication Date: 23 March 1995 (23.03.95)

(21) International Application Number: PCT/US94/09711

(22) International Filing Date: 2 September 1994 (02.09.94)

(30) Priority Data:
08/122,634 17 September 1993 (17.09.93) US

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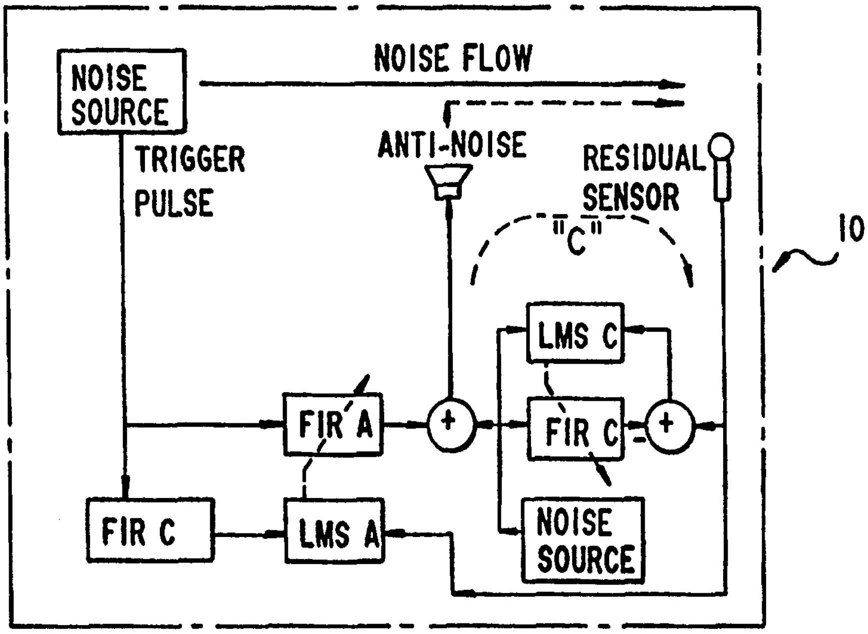
(81) Designated States: CA, JP, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: CAUSAL MODELING OF PREDICTABLE IMPULSE NOISE

(57) Abstract

A method and system (10) for causal modeling of predictable impulse noise which includes a sensor to detect the impulse noise, a means to process the sensor signal which includes a circuit to model an isolated response to govern the anti-noise acoustic response.



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CAUSAL MODELING OF PREDICTABLE IMPULSE NOISE

This invention relates to the causal modeling of impulse noise. Impulse noise occurs in many applications and is sometimes amenable to synchronous algorithms such as in "Selective Active Cancellation for Repetitive Phenomena", U.S. Patent No. 4,878,188 (when the repetition rate is consistent and not too slow as in Magnetic Resonance Imaging (MRI)) or the classical Feed Forward Algorithm (when a reference signal is available). The use of a noise model is discussed in U.S. Patent No. 4,153,815 (Chaplin et al) and further refined in U.S. Patent No. 4,417,098 (Chaplin et al) which are hereby incorporated by reference herein. The noise model in these patents, however, is the noise shape for one period of a periodic noise. In the present invention the noise model is maintained as an isolated instance of the natural response of the noise generation system when it is triggered once.

Nelson and Elliott "Active Control of Sound", Academic Press, 1992 which is hereby incorporated by reference herein, discuss the use of an adaptive feedforward cancellation system. When the reference signal is a trigger pulse, this system will cancel noise but will be slow in convergence. When the trigger pulses are close in time and cause impulse noise to overlap it will converge very slowly. When the noise is periodic the solution found by this system will be identical to that found by the system described in U.S. Patent No. 4,153,815. This periodic solution is not well behaved when the rate of the trigger signal suddenly varies whereas the solution found by the present invention handles the transient well. Canceling impulse noise in the general case (slow or inconsistent repetition rates) can be done more effectively when the algorithm is fully thought out. Unlike broadband noise, impulse noise can often be predicted from the previous impulse shapes and knowledge of the starting time (as in tonal noise cancellation) but this prediction must be done in the time domain for best performance.

This approach will compete effectively in several applications where a single channel multiple interacting sensors and actuators (MISACT) is a current solution, especially at those times when the MISACT assumption of a slowly changing rate is not valid. MISACT is shown and described in U.S. Patent No. 5,091,953 which is hereby incorporated by reference herein as is U.S. Patent No. 4,878,188.

Accordingly, it is an object of this invention to provide a method of causal modeling of predictable impulse noise.

This and other objects will become apparent when reference is made to the accompanying drawings in which

Figure 1 is a plot of a typical impulse noise,

Figure 2 is the plot of Figure 1 at four times the rate,

Figure 3 is the power spectrum plot of periodic noise,

Figure 4 is a schematic showing adaptive feed forward impulse noise canceling system,

Figure 5 shows an exhaust noise cycle,

Figure 6 is a schematic of an impulse noise canceling system, and

Figure 7 is a diagrammatic top view of an engine.

Background

Impulse noise is generated by suddenly occurring, high energy events. The energy released by the event then creates vibration and/or noise which tends to die out in a short time. The decay time taken is a function of the losses and resonances in the physical medium through which the noise or vibration passes. An example of an impulse noise with a rapid decay is firing a gun. An example of an impulse noise from a low loss (or high "Q") system and therefore having a slow decay is the sound of a bell or a cymbal.

Figure 1 gives an example of a typical individual noise impulse. The energy release at time zero causes the physical system to vibrate at a natural resonance frequency (which happens to be at one eighth of the sampling rate in this example). The vibration or noise then dies out exponentially and is down 40 dB by the 72nd sample period (after the 9th ringing cycle).

Many noise sources create impulse noise at regular intervals. The resulting tonal noise can and has been canceled by synchronous systems (MISACT). These noises can also be analyzed as being generated by a periodic impulse source.

Figure 2 shows the same impulse noise as in Figure 1 but repeated four times at a rate corresponding to one fourth of the natural ringing frequency. Note that the noise shape is not consistent until the third or fourth repetition as the "tails" of the earlier impulse noises accumulate to form the steady state "Noise Cycle" that we are familiar with in repetitive systems. A delayed version of the original impulse noise shape is dotted in with the last noise cycle for comparison.

Figure 3 shows the steady state of the power spectrum of this periodic noise. The primary noise is at the natural ringing frequency of the physical system. All of the frequency components are at multiples of the noise cycle (repeat rate) as expected in periodic noise sources. Note that the power at frequencies other than the ringing frequency is a function of the repeat rate and the decay time. If the repeat rate is fast compared to the decay time, very little energy is in the other frequencies. If the repeat rate is slow compared to the decay time, the other frequency components contain most of the noise power.

Referring now to Figure 4 it is shown how a classical Adaptive Feedforward (AFF) system can be used to cancel impulse noise. It will, however, be slow in adapting to changes in the noise. The block diagram shows a simplified AFF system 10 dealing with an impulse noise source.

The simplification is due to the fact that the anti-noise does not feed back to the reference signal (a trigger pulse synced to the start of each impulse). This eliminates the "B" filter which is normally used to eliminate feedback to the reference sensor in the general case.

The adaptive filter on the right of the diagram determines the anti-noise transfer function "C" by adding a low level test signal to the anti-noise output and correlating it with the residual signal. This measured "C" is then used to equalize the Filtered-X LMS update process in the main adaptive filter ("A") on the left of the diagram. The filter tap weights in "A" then continuously adapt to minimize the noise in the residual signal.

Improving AFF

The Steady State Answer

An analysis of the steady-state answer sought by the LMS algorithm can give insight into how AFF cancels noise. Let's denote the noise due to one impulse at the residual sensor as h(t) where t=0 is the time of the trigger signal. If we assume that the effect on "C" due to the processing of the residual signal is small (the effect of residual processing on "C" can be arranged to be small in most applications, it can also be directly accounted for since the major element is the anti-aliasing filter which is deterministic), then the filter coefficients converge to:

$$w_k = h_k \otimes c_k^{-1}$$

where $\otimes$ denotes the convolution operation which is the result of passing h_k through the inverse of "C". The convolution can also be stated as the output is a weighted sum over the "memory" in the filter and the filter (c^{-1}) "impulse" response quantifies the filter memory as a function of delay:

$$w_k = \sum_{j=0}^{k} h_j * c_{k-j}^{-1}$$

Note that c^{-1} only exists if the trigger signal is sufficiently in advance of the actual impulse noise. This is the usual requirement for causality seen in AFF systems when cancellation of non-tonal noise is desired. In non-causal situations (insufficient lead time) c^{-1} can only be approximated and is correct only at discrete frequencies.

Equalizing the Causal System

Since the AFF system directly measures "C" to do a Filtered-X LMS adaptation, c^{-1} can be directly calculated. This leads to the first suggested improvement. **Explicitly put c^{-1} in the anti-noise calculation and only adapt to find h(t), a model of the desired anti-noise**. The resulting system has two changes.

- There is a convolution operation to do between the LMS maintained h(t) model and c^{-1} to get the desired anti-noise. This can either be done as an explicit filter in series with the adaptive filter or implicitly as a recalculation of the weights themselves.
- The Filtered-X operation uses now "C" convolved with its inverse "C^{-1}" which tends to result in a pure delay thereby removing a convolution from the update equation.

With this set of changes the weights now model the impulsive noise itself as long as the overlap (in time) between repetitions can be ignored. If the adaptation is then shut off, the system will continue to do a good job of dealing with repetitive (overlapping in time) impulses as well Another advantage of this structure is that we have separated the effects of the noise path from those of the anti-noise path making it easier to understand the system's behavior.

Dealing with Periodic Impulse Noise

The AFF system described above will also cancel periodic impulse noise when allowed to adapt. It will find a solution that cancels the noise, but it will, in general, find the wrong solution. There are many solutions that will cancel the noise in the periodic case.

Two examples of solutions that cancel periodic impulse noise are:

- Set the weights to equal one isolated impulse noise. As shown before repetitive impulses will add to produce the necessary repetitive anti-noise. This is the desired solution as it is the only solution that remains accurate when the impulse rate changes.

- Set the weights equal to one cycle of the desired repetitive anti-noise and zero for all other times. This is one of many quasi-periodic solutions an LMS-based AFF system could find. They will all cancel the noise as long as the repetition rate does not change. When a change in rate occurs, the

AFF system will have to re-adapt to the new noise cycle shape before cancellation will occur. This re-adaptation may be slow, causing "burps" when the impulse rate changes suddenly.

Correcting this tendency to find the wrong answer is difficult since, in the steady state, there is no information in the noise to differentiate between the solutions. We only get information that points to the correct answer when the rate is changing or when the repetition rate is slow compared to the decay time.

The system can be biased toward the correct answer when the general shape of the noise pulse is known at design time. The weight update equations can be constrained to result in weights that follow the general shape. One set of constraints is to compute a running average of the energy in the weights over a short time period (long enough to average out ringing, but short enough to follow the envelope of the noise signal). This calculation can be used dynamically to bias the result to have the known shape.

Applicability of Impulse Cancellation

As discussed above there are two cases where the described system will tend to converge to the right answer and work well. They both depend on a trigger signal that is sufficiently in advance of the noise and that the impulse shape is consistent from pulse to pulse. These cases are:

Constantly varying noise rate - As long as the rate of the noise is constantly varying the adaptation rate can be set to average over several impulses and the system will do a good job.

Non-overlapping impulses - When the impulses die out between repetitions the system is well behaved.

There is one other case where this system works well. This is the periodic case where our MISACT solution also works well. Here there is no need for an early trigger and the system should compete effectively with the MISACT solution.

MUFFLER: AN APPLICATION

Internal combustion engines are impulse noise sources and are a good application for impulse cancellation. This approach will be effective for Industrial applications especially where the noise complexity is too high for other algorithms. It will also work for automotive applications. The following analysis pertains to muffler applications.

The exhaust noise in a vehicle can be approximated by an impulse of energy at the opening of the exhaust valve. See Figure 5 for a plot of the noise cycle.

The amplitude of the pulse is a strong function of the engine torque. The timing is fixed WRT the rotation (physical) of the crank (may need to be somewhat variable in new engines with variable valve timing). Therefore use eight repetitions of this model (one for each cylinder) tied to sync.

See Figure 6 for a flow diagram of the signal processing where:

θ_0	is the phase indeterminacy and handle for variable valve timing
$k_1 \rightarrow k_N$	are differential output levels (cylinder compression difference, etc.) (Slowly Varying)
$\tau_1 \rightarrow \tau_N$	is differential delays in exhaust headers (Slowly Varying)
k_0	is noise level and is related to torque (Rapidly Varying)
AFF filter	models the exhaust pipe with compensation for the transfer function of the output transducer (Slowly Varying, mainly due to temperature). The filter will also compensate for any error in pulse shape.

We therefore have only 2(N+1) variables (N = number of cylinders) and only one of those must be adapted quickly.

The earlier systems used a generic noise model that has no a priori knowledge of how the noise will change as a function of conditions. It must therefore adapt quickly as conditions change and during time of rapid change, some cancellation reduction occurs.

A MISACT model: 2 weights per harmonic

64 harmonics at low RPM	128 weights
32 harmonics at high RPM	64 weights

therefore, at each iteration of the loop (noise cycle - 2 revs) there must be an update of the 64 or 128 weights and the system tracks the noise cycle period.

From the operation of this model there is no relationship between the harmonics and their behavior as a function of RPM and torque.

Therefore, the modified AFF system has only one rapidly varying parameter to deal with while the synchronous system has more than 60. It will therefore tend to behave better when engine conditions change rapidly.

CLAIMS

1. A method of canceling impulse noise in an active noise cancellation system, said method comprising

   triggering an isolated trigger to provide a response in a sound source,
   measuring a single isolated system response to the isolated trigger
   modeling of said single isolated response, and
   using said model to generate the required anti-noise.

2. A method as in claim 1 wherein said impulses are periodic and said model generates periodic anti-noise.

3. A method as in claim 1 wherein said impulses result in overlapping responses and said model generates a anti-noise in a concurrent and opposite manner.

4. A method as in claim 1 wherein said noise cancellation system is an adaptive feedforward system.

5. A method as in claim 1 wherein said noise cancellation system is an adaptive feedforward system with a filter means and the analysis of the steady state answer of said transfer function is

$$w_k = h_k \otimes c_k^{-1}$$

   where $\otimes$ denotes a convolution operation which results in passing h_k through the transfer function "C" and the filter (c^{-1}) impulse response quantifies the filter memory as a function of delay.

6. A method as in claim 5 where c^{-1} is explicitly put into the anti-noise calculation and only adapted to find h(t), a model of an isolated example of the desired anti-noise impulse.

7. A method as in claim 6 where the adaptation rates of the coefficients of h(t) are adjusted to bias the shape of h(t) to have smoothly decreasing energy as time increases so as to minimize transient errors after a period of constant repetition rate.

8. An active noise canceling system for canceling impulse noise comprising

sensor means to sense said impulse noise and produce a signal responsive thereto,

processor means to receive said signal and produce an anti-noise signal in response thereto,

transducer means adapted to produce anti-noise acoustics in response to said anti-noise signal,

said processor means including means to measure a single isolated system response, and

means to model said single isolated response,

whereby said processor means is adapted to use said single model isolated response in generating the required anti-noise.

9. A system as in claim 8 wherein said noise cancellation system is an adaptive feedforward system with a filter means and the analysis of the steady state answer of said transfer function is

$$w_k = h_k \otimes c_k^{-1}$$

where ⊗ denotes a convolution operation which results in passing h_k through the transfer function "C" and the filter (c^{-1}) impulse response quantifies the filter memory as a function of delay.

10. A system as in claim 9 where c^{-1} is explicitly put into the anti-noise calculation and only adapted to find h(t), a model of an isolated example of the desired anti-noise impulse.

11. A system as in claim 10 where the adaptation rates of the coefficients of h(t) are adjusted to bias the shape of h(t) to have smoothly decreasing energy as time increases so as to minimize transient errors after a period of constant repetition rate.

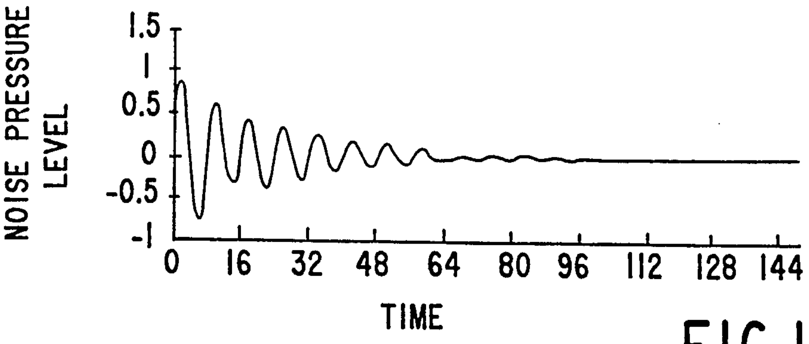

FIG.1

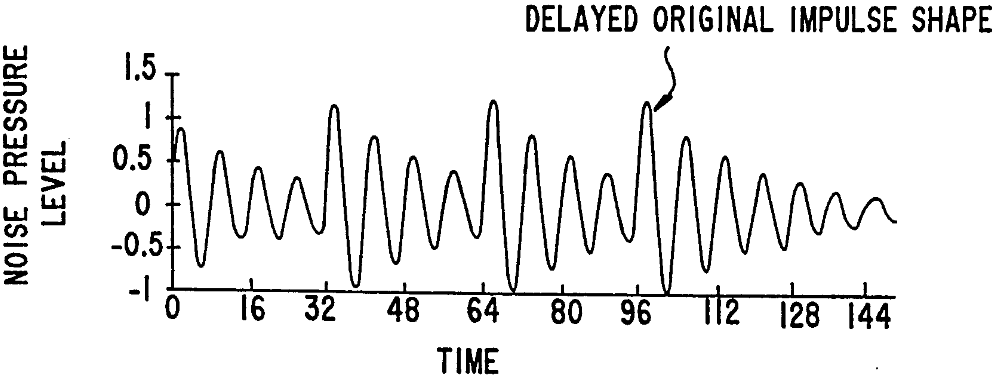

FIG.2

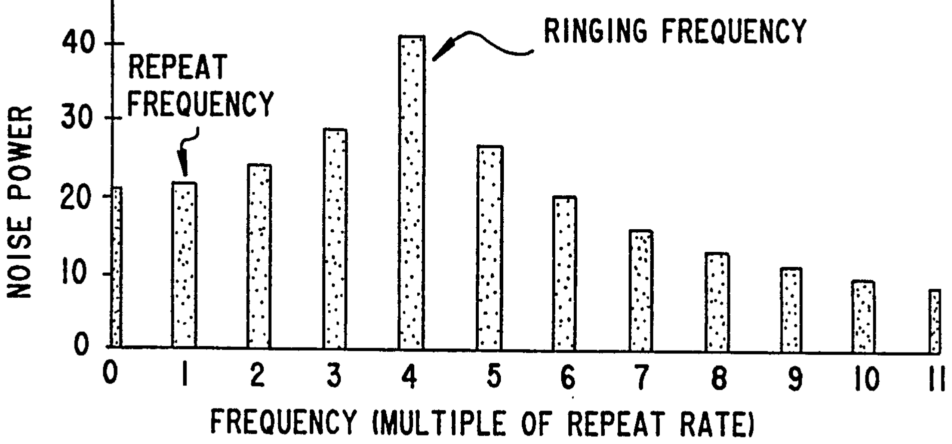

FIG.3

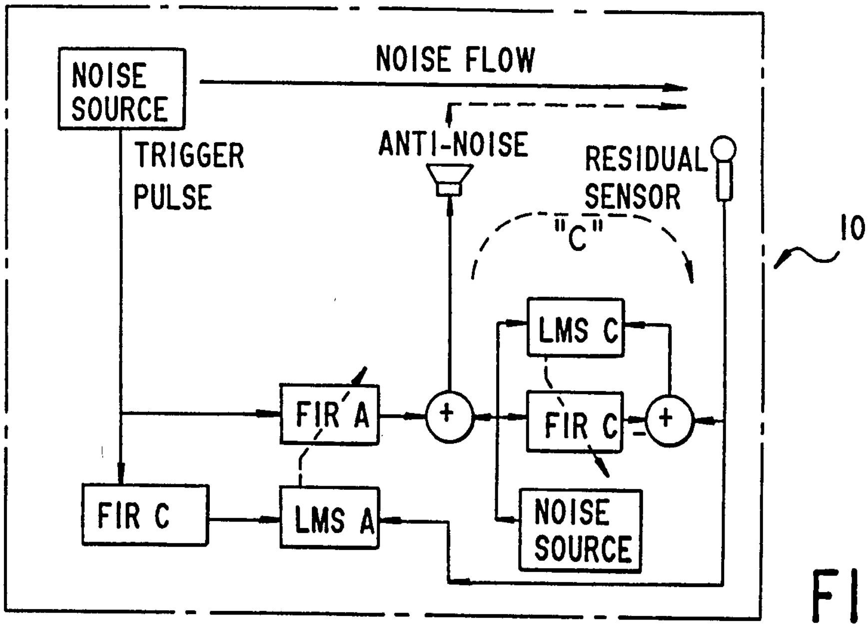

FIG.4

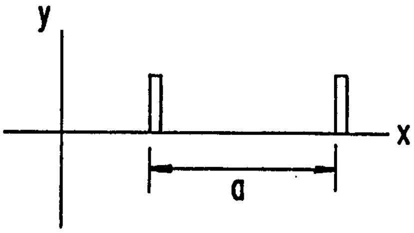

FIG.5

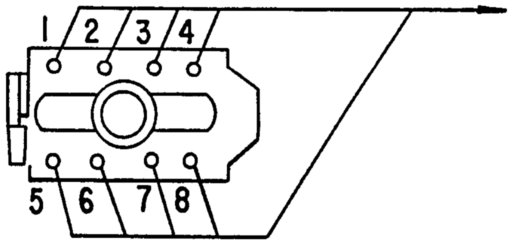

FIG.7

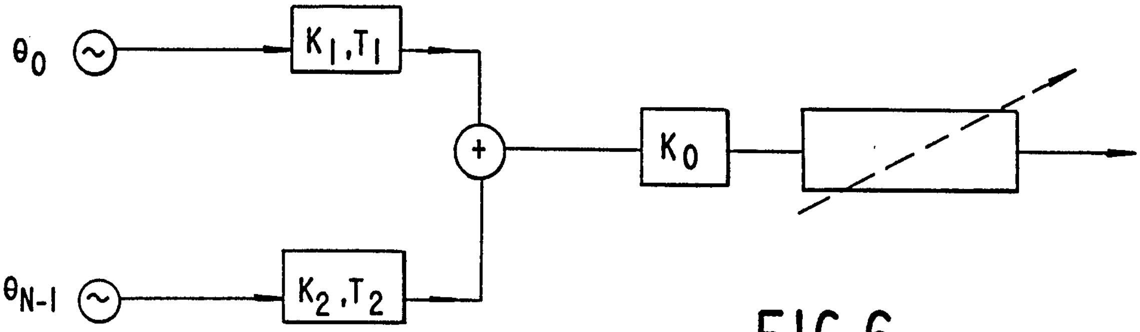

FIG.6

INTERNATIONAL SEARCH REPORT

International application No.
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A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :G06F 17/50
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According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 364/574,508,724.19;381/71,94;367/1,135,137,901;370/32.1;244/1N

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Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US, A, 5,117,401 (Feintuch) 26 May 1992, see Abstract, Fig.4, col.7 lines 41-68, col.8 lines 1-5.	1-11
Y	US, A, 5,187,692 (Haneda et al) 16 February 1993, see Abstract, Fig.16, col.23, lines 20-44.	1-11
A,P	US, A, 5,278,780 (Eguchi) 11 January 1994, see Abstract and front drawing.	1-11
A,P	US, A, 5,313,407 (Tiernan et al) 17 May 1994, see Abstract and front drawing.	1-11
A,P	US, A, 5,251,262 (Suzuki et al) 5 October 1993, see Abstract and front drawing.	1-11

☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US94/09711

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US, A, 5,140,640 (Graupe et al) 18 August 1992, see Abstract and front drawing.	1-11
A	US, A, 5,146,505 (Pfaff et al) 08 September 1992, see Abstract and front drawing.	1-11
A	US, A, 5,033,082 (Eriksson et al) 16 July 1991, see Abstract and front drawing.	1-11
A	US, A, 4,987,598 (Eriksson) 22 January 1991, see Abstract and front drawing.	1-11