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ACTIVE NOISE AND VIBRATION CONTROL (*ANVC*): CURRENT TRENDS, PERMANENT AIMS AND FUTURE POSSIBILITIES

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The main purpose of this report is to provide a deaper and more adequate understanding of *ANVC*. A literature of about 500 papers is now available and has been analysed: *ANVC* is now developed in many directions; many experiments have been done, proving that several kinds of noise and vibration can be attenuated substantially by active devices. Industrial and commercial exploitation seems a matter for tomorrow.

An epistemological obstacle is emphasized, which may be called "anticausality" or teleonomy. A shift of paradigm (in KUHN's sense) seems to be useful or even necessary to get a fair understanding of how to solve a practical active control problem.

The author recalls the origins of his own method, which had been applied and developed in acoustics by G. MANGIANTE and G. CANÉVET, becoming then the *JMC* theory. This theory has been recently reformulated in a set of three theorems on "field reshaping". The first theorem of Field Reshaping is analysed. It leads to a very general "designer's equation" which can be considered as the key to most active control systems. Two appendixes (Fig. 2–4) show how to meet some requirements of the *JMC* theory: a) location of the main sensor in the closest neighborhood of the antisource, i.e. using a feedback suppressor; b) digitizing the system for easier adaptative checking.

Plan:

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1. Introduction

1.1. Vocabulary, notations and abbreviations

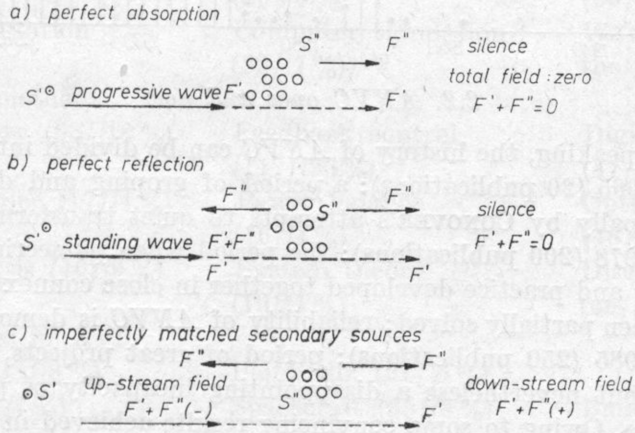
ANC: Active Noise Control, or: Active Noise Cancellation
ANA: Active Noise Absorption, but **not** "Active Noise Attenuation"!
ANR: Active Noise Reflection, but **not** "Active Noise Reduction"!
AVC: Active Vibration Control, or: Active Vibration Cancellation
AVD: Active Vibration Damping (for vibrations which propagate across elastic media)
AVA, (resp. *AVR*): Active Vibration Absorption (resp. Reflection)
S': primary source of noise or vibration
F': primary field (radiated by S')
S'': secondary source (*s*), introduced either by the Huygens Principle (HP) or by the Principle of Active Absorption (PAA)
F'': secondary field (radiated by S'')
OP: *Physical* operator connecting a field F with its source (*s*): $OPF = S$ (hence also: $OP\,F' = S'$ and $OP\,F'' = S''$)
OR: *Radiation* operator expressing a field F in terms of its source (s): $OR\,S = F$ (hence also: $F' = OR\,S'$ and $F'' = OR\,S''$).

1.2. A first practical reason for promoting ANVC

The conventional approach to noise and vibration abatement is to passively absorb the vibratory energy, i.e. convert it into heat via viscous flow. In most cases, the total energy involved in noise or unwanted vibrations is very small, so that passive absorption will have negligible impact on the ambient temperature. The technology for passive attenuation is well developed and is extensively employed in mufflers, absorptive wall panels and damping coatings for vibrating structures. The absorption efficiency for a given passive device generally increases with the frequency of the noise; and for frequencies above 200 Hz passive absorption is the usual and cheapest solution. But for very low frequen, cies, passive attenuators become very large and costly. Hence, we reach the first reason for supporting active methods of noise and vibration abatement.

1.3. *Preliminary sketches of wave control by secondary sources*

Three cases are emphasized: perfect absorption, perfect reflection and imperfect matching. It is important to note that these sketches are valid for passive as well as for active control. Passive secondary sources are considered to be induced in some absorbing or reflective medium by a convenient natural process. Active secondary sources are to be created artificially with the help of some adequate device.



Some degree of mismatch is allowable provided that the downstream field $F'+F''(+)$ remains small comparatively with the "incident" field F'; *up-stream* and *down-stream* is meant relatively to the set of S'' sources. The hypothesis that the set of S'' is perfectly transparent to the field F' is not essential: suffice to consider that in the down-stream area F' means the field radiated by S' with account of the presence of the set S''.

2. Current trends in *ANVC*

The most extensive compilation on *ANVC* literature has been drawn up by D. Guicking, who recorded 457 reference papers from 351 authors between 1933 and the end of 1984. Analysis of this bibliography provides good information on the evolution and present state of *ANVC*.

2.1. Evolution of the interest in ANVC

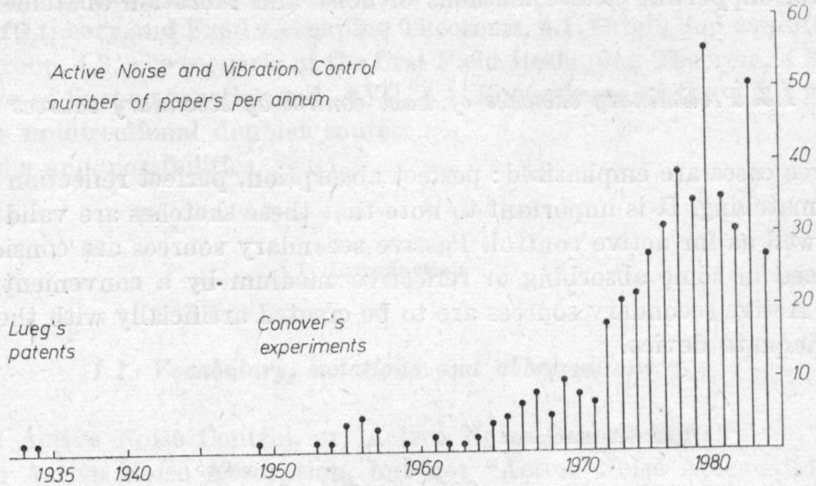


Fig. 1

2.2. ANVC once and now

Roughly speaking, the history of *ANVC* can be divided into 3 periods:

1° 1933–1965 (20 publications): a period of groping and disappointment, marked principally by Conover's attempts to quiet transformer hum.

2° 1966–1978 (200 publications): the period when pioneering became successful; theory and practice developed together in close connexion; major problems have been partially solved; reliability of *ANVC* is demonstrated.

3° 1979–1985 (250 publications): period of great projects, impressive demonstrations but nevertheless a disappointing incapacity of producing commercial devices. Owing to some convincing results achieved in the preceeding period, *ANVC* is (definitively?) recognized as a technique of real importance. Several new systems have been developed; more impressive demonstrations have been conducted; serious programs are under way in several noise-abatement hardware companies and industries with noise problems show an increasing interest in *ANVC*.

2.3. The most productive authors

(name)	(country)	(number of papers)	(speciality)
Balas	USA	13	Feedback control of structures
Bschorr	D	16	*ANC*
Eghtesadi	Iran	13	*ANC* (experiments)
Fedoryuk	USSR	8	*ANC* (theory)
Guicking	D	11	*ANC*
Jessel	F	20	*ANVC*
Kido	J	10	*ANC* (automatic control)
Leventhall	GB	17	*ANC*

MANGIANTE	F	12	*ANC*
MEIROVITCH	USA	17	Active control of dynamic systems
OZ	USA	11	Active control of dynamic systems
TARTAKOVSKII	USSR	16	*ANVC*
WARNAKA	USA	8	*ANC*

2.4. Keyword analysis

a) Kind of papers

Bibliography (19//4 %)	Historical (38//8 %)	
Overview (59//13 %)	Context papers (24//5 %)	
Fundamentals (76//17 %)	Theory (226//50%)	Problems (18//4 %)
Experimental (144//32 %)	Model experiment (25//5 %)	Modelling (26//6 %)
Model computation (46//10 %)	Computer simulation (32//7 %)	Waveform synthesis (18//4 %)

b) Means and methods

Control theory (83//18 %)	Feedback control (117//26 %)	Digital control (47//10 %)
Energy balance (17//4 %)	Power balance (16//4 %)	Optimization (46//10 %)
Modal analysis (40//9 %)	System theory (19//4 %)	Discretization (46//10 %)

c) Special topics in *AVC*

Beam vib. (38//8 %)	Plate vib. (21//5 %)	
Aircraft (34//7 %)	Spacecraft (35//8 %)	Buildings and bridges (31//7 %)
Structures (94//20 %)		
Vib. suppression (121//27 %)	Vib. dampers (20//4 %)	Vibr. insulation (18//4 %)

d) Special topics in Acoustics and *ANC*

Transformer noise (24//5 %)	Structure borne sound (37//8 %)	Noise (37//8 %)
Monopole (39//9 %)	Dipole (31//7 %)	Tripole (25//6 %)
1D (one-dimensional 117//26 %)	2D (5//1 %)	3D (91//20 %)
Duct (58//13 %)	Exhaust (20//4 %)	Turbulence (20//4 %)
Loudspeaker (18//4 %)	Headset (18//4 %)	

2.5. Towards a better understanding of ANVC

The prime aim of this report was to provide a better understanding of active confinement of noise and vibration. Usefulness of such an intention becomes evident as soon as one takes a look at the above panoramic view upon the work done currently in the field of *ANVC*. In spite of many encouraging results, its present state does not seem fully satisfying: effort is too dispersed and too fragmentary. An increase of interdisciplinary cooperation, among individuals with different backgrounds and skills, would surely prove very helpful for future development. Nevertheless a basic epistemological obstacle remains still to be removed: active control is a new sort of generalized feedback control; both appeal to a basic notion of intentionality and finality, whose vital importance in RESEARCH and DEVELOPMENT cannot remain over-looked any longer. Hence the next short excursion into epistemology.

3. A short excursion into epistemology

3.1. Waldhauer's "*anticausal analysis*"

In a book entitled "Feedback", Fred D. Waldhauer introduces a new way of building up feedback theory and design. Instead of computing the output as a function of the input (as in the main causal analysis), he considers the output as known or given and expresses therefore the input in terms of the output. This new approach he calls "anticausal analysis" and shows in detail over more than 600 pages the benefits of it in designer's comfort and synthesis efficiency. Unfortunately he writes only a few lines on the philosophical aspects of his innovation. In fact Waldhauer's method introduces really a *paradigm shift* (according to Kuhn's terminology). Novelty and importance of such an epistemological revolution can be safely compared to that of Copernicus. It is only to be hoped that anticausal analysis will be accepted by the world of science and technology in less time than the heliocentric system!

3.2. Technology as the science of teleonomy and "purposeful thinking"

Epistemology is the science of sciences. In the same sense, technology should be not only the scientific justification of practical know how and technica practice, but also the very science of all the applied sciences, including their industrial and commercial developments. As in marketing and other commercial or economical sciences, anticausal approach becomes essential. Evidently Noise and Vibration Control belongs to applied mechanics. As control becomes active, with feedback effect, acceptance of teleonomy and anticausality must follow inavoidably.

3.3. Alternation causality-anticausality

Anticausal analysis, which proceeds from effect to cause, is fairly complemental to the common deductive causal analysis which proceeds from cause to effect. Both can be coupled and used alternatively in close connexion. Such an alternating approach will be emphasized in the next section in the framework of a very general problem on wave propagation. Thus will be obtained a very robust and versatile *designer's equation* for *ANVC*.

4. *JMC* theory and field reshaping theorems

Over 30 papers were published between 1968 and 1980 by the *JMC* group composed by Jessel, Mangiante, Canévet and a few other students and engineers working on *ANC*.

4.1. *Origin and evolution of the JMC group*

As soon as 1954, while he was working on diffraction for a thesis under the direction of Louis de Broglie (the inventor of wave mechanics) and René Lucas (one of the discoverers of the diffraction of light by ultrasound), Jessel realized that Huygens' Principle (HP) leads by complementarity to a principle of active wave confinement. In 1965 with the help of René Lucas, Jessel was appointed at the Marseilles CNRS Laboratories with a view applying his idea of active confinement in acoustics. The *JMC* group started its work in October 1967 and soon obtained positive results on active absorption of a sinus sound wave in a duct. The group carried on its activity during about ten years, then it has been progressively dismantled for quite not scientific reasons. Since 1980 a different direction has be given in the research done in Marseilles on *ANC* and since 1981 Jessel works alone on qure theoretical subjects: general system theory, holophony and *field reshaping*. The latest subject, which embeds very many applications, provides now the most general approach to *ANVC* and will perhaps lead to a more convincing understanding of *ANC* and *AVC*.

4.2. *The scenario of the first Field Reshaping Theorem*

As already told above, anticausal reasoning will alternate here with normal causal deduction.

a) The first step is causal: one is given a primary source S' and its radiated field F' with the connecting equation

$$OP\,F' = S'. \tag{1}$$

But one observes that F' is not convenient in some part of the space where it is measured (or computed by the inverse connection $F' = ORS'$).

b) Second step: introduction of *finality*, by defining a "required" field F which may be given everywhere or even only in the parts of space where it is different from F'. The problem now is to obtain F not from completely new sources S but from the source S' (possibly modified in a convenient way) with the help of some additional (secondary) sources S''. Therefore we now introduce an operator M "modifier" which can be applied to S' as well as to F': we deduce M from F and F' by writing

$$F = M\ F' \tag{2}$$

and, if necessary, we give M a convenient extension so M can be applied to S', leading then to the new source MS'.

c) Third step: anticausality leads us now to look for an equation whose solution is the required field F: the nature of the physical phenomena remaining inaltered, this equation will use the same operator OP. We consider therefore $OP\ F = OP\ M\ F'$. But than we must observe that usually $OP\ M \neq M\ OP$: the two operators do not commute. Therefore we have to introduce another set of sources: secondary sources S''. Then we will get

$$OP\ F = OP\ M\ F' = M\ S' + S'' = M\ (OP\ F') + S'' \tag{3}$$

which leads to

$$S'' = OP\ M\ F' - M\ OP\ F' = (OP\ M - M\ OP)F'. \tag{4}$$

Eq. (4) can be called the ***designer's equation*** for many technical problems including those of *ANC* and *AVC*.

Note that the approach contains really a good amount of anticausality, as we start here from a given field F in the course of looking for the sources (the causes) that will be the most convenient to produce it.

d) Following steps. The alternation can be carried on: usually the sources S'' can be put together only approximatively; such approximate sources S''_0 can in turn be used as primary sources for a second iteration. And so on ...

e) From (3) and (4), together with an explicit knowledge of $OR = OP^{-1}$, we obtain a formula which generalizes KIRCHHOFF's one

$$F = MF' = OR[MS' + (OP\ M - M\ OP)F']. \tag{5}$$

Observe also that GREEN's formula is useless here. In fact another and simpler identity plays here the role of the GREEN's formula

$$OP\ M\ F' = M\ OP\ F' + (OP\ M\ F' - M\ OP\ F'). \tag{6}$$

4.3. The special case of linear acoustics and ANC

For meeting linear acoustics, one has to specialize conveniently the operator OP, the field F' and the sources S'. The can be done as follows

$$F' = \begin{pmatrix} p' \\ v' \end{pmatrix}, \quad S' = \begin{pmatrix} q' \\ f' \end{pmatrix}, \quad OP = \begin{pmatrix} \delta_t & \text{div} \\ \text{grad} & \delta_t \end{pmatrix} \tag{7}$$

which corresponds to the system of equations

$$\delta_t p' + \operatorname{div} v' = q' \quad \text{and} \quad \delta_t v' + \operatorname{grad} p' = f'. \tag{8}$$

As for operator M, it will be given the constant value 0 in a part E_0 of space which is to be silenced. In another part E_1 it will, say, be given the constant value 1, as we cannot or will not alter the primary field in this part E_1 of space. We therefore write M as a matrix

$$M = \begin{pmatrix} m & 0 \\ 0 & m \end{pmatrix}, \tag{9}$$

where m is a continuous function with value 0 in E_0 and 1 in E_1.

Formula (4) provides now the *"designer's equations*

$$q'' = v' \cdot \operatorname{grad} m \quad \text{and} \quad f'' = p' \cdot \operatorname{grad} m. \tag{10}$$

This means that the *ANC* secondary sources S'' are made, according to the *JMC* theory, of monopole sources q'' and of force vector sources f'', the latest being equivalent to dipoles. When necessary, we shall emphasize them as *JMC sources* or *JMC antisources.*

JMC antisources may be more complicated than "tripoles" (monopole+dipole). When the velocity vector v' is no more collinear with grad m in (10), one will have to complete the system (8) by an equation of irrotationality for v': rot $v' = 0$. Then, by reshaping of v', a quadripolar source will appear: $g'' = v' \cdot \operatorname{grad} m$.

4.4. Equivalence of the JMC tripole with other unidirectional sources

M. A. Swinbanks' double ring source can be symbolically presented as a sum of two unequal monopoles: $[Q_1(x-a)+Q_2(x+a)]$. The *JMC* tripole can likewise be $[q_1(x-a)+q_0(x)-q_1(x+a)]$. It is possible to shift over the short distance a the central monopole q_0 of the *JMC* source. Mathematically, the shift can be accounted for by replacing the diagonal mm of the matrix (9) by $m_p m_v$ i.e. by reshaping p' and v' in slightly different manners. The *JMC* tripole would thus become $[q_1(x-a)+q_0'(x+a)-q_1(x-a)]$ result which can easily be identified with the Swinbanks' doublet. Note that Angevine also simplified the *JMC* tripole to a couple of asymmetric loudspeakers.

5. Aims and possibilities

The main question concerning Active Control, on Vibrations as well as noise, is that of its feasibility and economical interest. For its theory cannot be falsified, except by requiring the falsity of one or another of the firmest axioms in mechanics and classical physics. But the connectio is new and apparently some taboo subject has been evoked. Aims and claims of the *JMC* theory are straightforward conclusions directly deduced from its *designer's equations*: Wave Reshaping and consequently *ANC* and *AVC* must work for mechanical waves of any kind and in any medium, and for non-linear phenomena as well as for the linear ones. As for the waveforms, the easiest to cancel is of course the sines and the sum of sines. Then the stationary noises with relatively narrow frequency bands and eventually the non-stationary broadband noise. The difficulties of materializing the *ANC* antisources are of technical origin. For tight

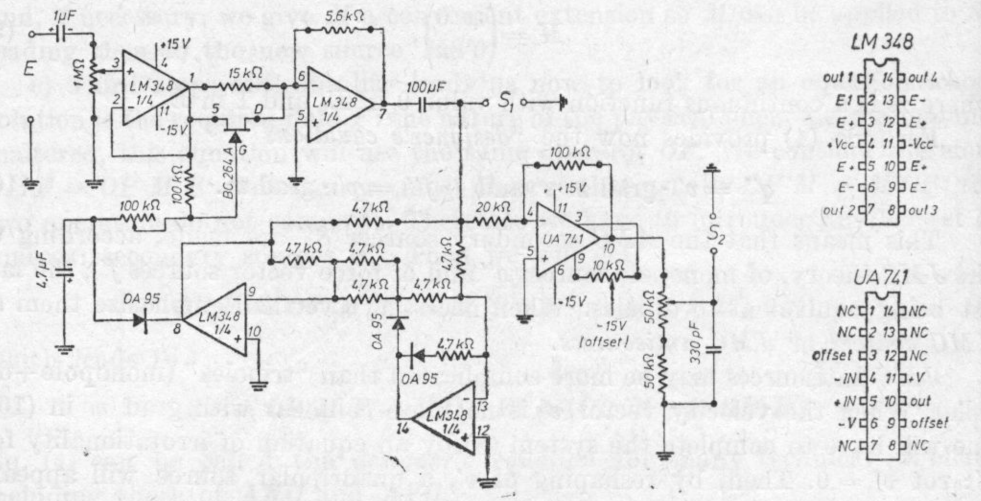


Fig. 2. Amplifier with feedback suppressor, after Th. Angelini (formerly in the *JMC* group
E: input; S_1 output without suppression; S_2 output with suppression

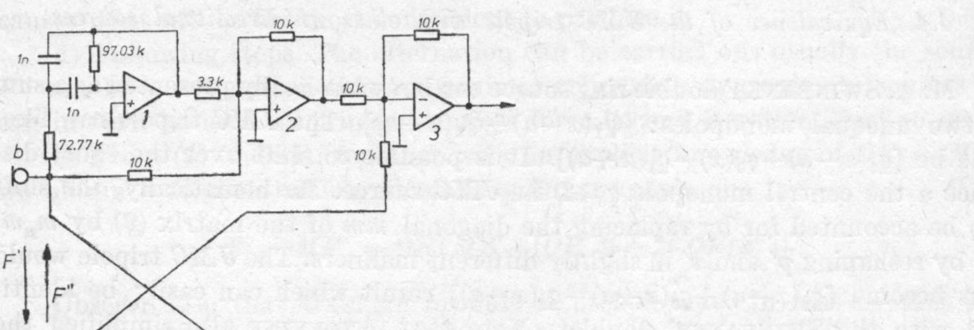


Fig. 3. A standing wave suppressor for suppressing the feedback between antisource and sensor (after M. Rollwage). Distance $(a, b) = 10$ cm. Primary wave (F') comes from above, while the secondary wave (F'') comes from below

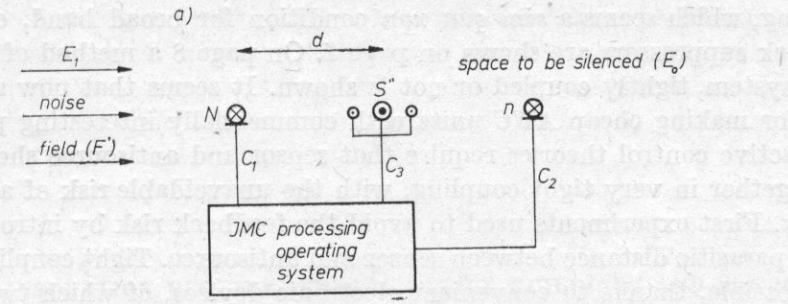


Fig. 4a. The system of antisources S'' is fed through a convenient operating system whose example is given in *b*). *N* is the main sensor (possibly a set of microphones measuring not only the incident pressure p' but also the particle velocity v'). *n* is another sensor or microphone for checking the efficiency of the antinoise system (N, S'') and possibly improving it by adaptative action. Channels *C1*, *C2* and *C3* (or C_1, C_2 and C_3) are respectively for the data concerning *N* (main *JMC* sensor), *n*, the checking microphone and S'', the *JMC* antisource

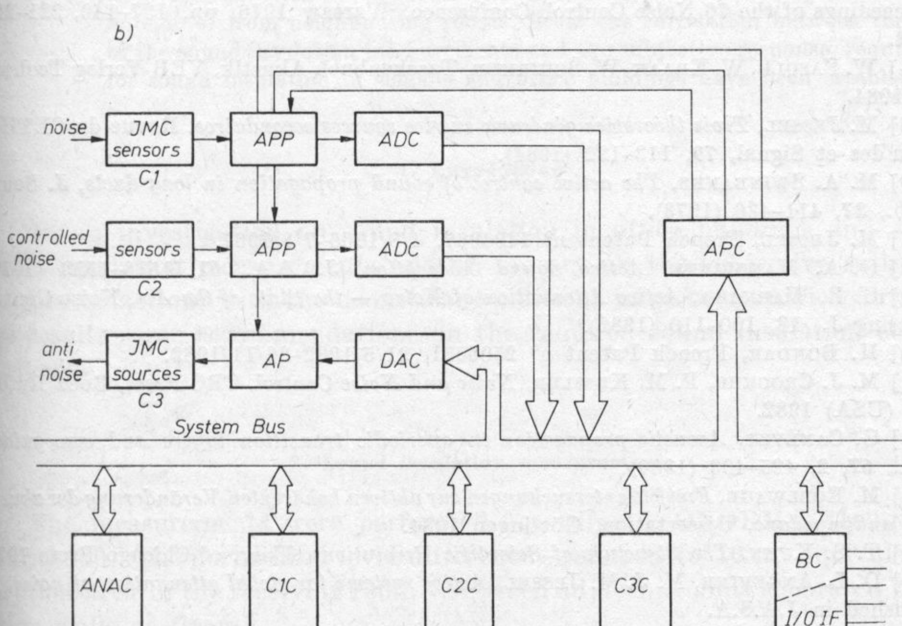


Fig. 4b. Details of the *JMC* operating system (according to G. Mangiante). Preprocessing means filtering, sampling and preamplifying (*APP*). Channels *C1*, *C2* and *C3* can operate in parallel, to speed up the process. Abbreviations: *APP*: Analogic "PreProcessor"; *ADC*: Analogic-Digital Converter; *AP*: Analogic Processor; *DAC*: Digital-Analogic Converter; *APC*: Analogic Processor Controller; *ANAC*: Active Noise Absorber Controller; *C1C*, *C2C*, *C3C*: Channel 1, 2, 3 Controller; *BC*: Bus Controller; *I/O IF*: Input/Output InterFace

coupling, which seems a *sine qua non* condition for broad band, examples of feedback suppressors are shown on page 7. On page 8 a method of digitzong a *JMC* system, tightly coupled or not is shown. It seems that now all elements exist for making cheap *ANC* units with commercially interesting possibilities. Most active control theories require that sensor and antisource should be placed together in very tight coupling, with the unavoidable risk of a ringing feedback. First experiments used to avoid the feedback risk by introducing a so to say parasitic distance between sensor and antisource. Tight coupling becomes now possible, thanks to convenient electronic devices, of which two examples are shown on this page. Papers on tight coupling have also been published by H. G. LEVENTHALL and W. HONG. ROLLWAGE'S device was used in an active system for changing the acoustical impedance of a wall: the wall can be made perfectly absorbing as well as reflecting to a required degree!

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Comments:

JESSEL'S patent [7, 1966] concerns an *ANC* system with adaptative checking.

BONDAR'S patent [10, 1982] concerns a cold plasma loudspeaker which is now developed in an improved form. Such systems of loudspeakers, with very good performances also at very low frequencies, would be very convenient as *ANC* antisources.