JMC method applied to active control of sound
Theoretical extensions and new source configurations

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Abstract

The *active control of sound* can be used to control the acoustics of interior spaces, to reduce the sound radiation of machines and equipment, to decrease and even to refine noise in a more comfortable form in, e.g., ducts and vehicles. The *JMC method*, developed by Jessel, Mangiante and Canévet, is a systematic tool in the active control of sound. It is applied mostly by using scalar weighting, in which all the first-order field quantities and primary source strengths are weighted similarly. In this thesis, a *modified JMC method* is developed, in which the primary sources remain unchanged in all cases, the situation being more similar to a practical one. On the basis of the modified JMC method, the *vector and dyadic weightings* are defined, the former weighting the sound pressure and particle velocity independently, and the latter also changing the direction of the particle velocity. These new weightings increase the possibilities in field reshaping. In the JMC method, three types of secondary sources are needed: monopoles, dipoles and quadripoles. It is found that in multi-source configurations, the last ones are automatically generated by the dependence of the dipole distribution on the lateral coordinates. Four *three-unit approximations* of the *JMC element* (i.e., detector-actuator combination according to the JMC method) are developed, in which one of either the primary field quantities or the secondary source quantities is approximated by the help of a field impedance function. For *waveguides* (e.g., ducts), ideal unidirectional *three-element and two-element JMC source* configurations and their approximations are discovered. The inter-channel delay in the control structure of the two-element actuators may be optimized downstream or upstream, or omitted altogether. Especially the last case turns out to be advantageous in the practical implementation of digital control systems. The adaptive JMC structures for the new ideal two-element solutions are presented. The results of this thesis enlarge the possibilities in the active control of sound and facilitate more useful applications to be realized in ducts and three-dimensional spaces.

Preface

The work of this thesis has been carried out at Occupational Safety Engineering Laboratory of VTT (nowadays VTT Automation, Safety Engineering), and VTT Building Technology, Building Physics, Building Services and Fire Technology; Acoustics. The results have been obtained through an internal research project in 1987–1989 *(Application of the intensity technique in the noise control of buildings, machinery and ships)*, AKTIVA project *(Active control of sound)* in 1995–1997 financed partly by Finnish industry and Tekes, and FACTS project *(Film Actuators and Active Noise Control for Comfort in Transportation Systems)*, an ongoing EU project started in 1996 in Brite-Euram III programme.

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List of publications

"JMC method applied to active control of sound – Theoretical extensions and new source configurations"

This thesis comprises the present summary and the following publications which are referred to with Roman numerals:

I   Uosukainen, S. Modified JMC method in active noise control. Inter-Noise 90 (International Conference on Noise Control Engineering), proceedings. Gothenburg, Sweden: Acoustic Society of Sweden, 1990. Vol. 2. Pp. 1289–1292. ISSN 0105-175X. ISBN 91-7848-224-0.

II   Uosukainen, S. Modified JMC method in active control of sound. Acustica united with acta acustica 1997. Vol. 83, no. 1, pp. 105–112. ISSN 0001-7884.

III   Uosukainen, S. JMC method in active control of sound. ISMA23 (International Conference on Noise and Vibration Engineering), proceedings. Leuven, Belgium: Katholieke Universiteit Leuven, 1998. Vol. 2. Pp. 729–736. ISBN 90-73802-64-4.

IV   Uosukainen, S. & Välimäki, V. Unidirectional JMC actuators in the active attenuation of noise in ducts. Acustica united with acta acustica 1999. Vol. 85, no. 1, pp. 63–77. ISSN 1436-7947.

V   Uosukainen, S. & Välimäki, V. Unidirectional JMC actuators and their approximations in the active attenuation of noise in ducts. VTT Publications 341. Espoo, Finland: VTT, 1998. 88 p. + app. 12 p. ISSN 1235-0621 (soft back edition), 1455-0849 (URL: http://www.inf.vtt.fi/pdf/). ISBN 951-38-5223-7 (soft back edition), 951-38-5224-5 (URL: http://www.inf.vtt.fi/pdf/).

VI   Välimäki, V. & Uosukainen, S. Adaptive design of a unidirectional source in a duct. ISMA23 (International Conference on Noise and Vibration Engineering), proceedings. Leuven, Belgium: Katholieke Universiteit Leuven, 1998. Vol. 3. Pp. 1253–1260. ISBN 90-73802-63-6.

Contents

Appendices of this publication are not included in the PDF version.
Please order the printed version to get the complete publication
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List of symbols

a	dipole weighting for an actuator element in a waveguide
b	monopole weighting for an actuator element in a waveguide
c_0	speed of sound in a fluid at rest
d	distance between outermost actuator units in a waveguide
e_i	error signal ($i = 1, 2, \ldots$)
f_s''	surface secondary dipole distribution (force / unit area)
g_s''	surface secondary quadripole distribution
H_i	transfer function (for detectors $i = 1, 2, 3$, for actuators $i = 4, 5, 6$)
$H_Z, H_{1/Z}$	impedance approximation, admittance approximation
k	wave number (ω/c_0)
L	distance between the detector and the actuator unit in a waveguide
M	weight operator
p	sound pressure
p_i	incoming sound pressure at the actuator unit in a waveguide
p_{res}	residual sound pressure
p_+	sound pressure radiated by the actuator unit downstream in a waveguide
p_-	sound pressure radiated by the actuator unit upstream in a waveguide
q_i	p_i scaled to a volume velocity quantity
q_L	incoming sound pressure at the detector in a waveguide scaled to a volume velocity quantity
q_S''	surface secondary monopole distribution (volume velocity / unit area)
q_0	volume velocity of the actuator unit in the middle of a three-actuator system in a waveguide
q_1, q_2	volume velocity of the first and last actuator unit in a waveguide
t	time
u_x, u_T	particle velocity in x-direction and in tangential direction
V_i	output voltage of a detector ($i = $ "p", "u_x", "u_T") or input voltage of an actuator element ($i = $ "q", "f", "g")
x	Cartesian coordinate
λ	wavelength of sound
τ	propagation acoustic delay between the outermost actuator units in a waveguide
τ_L	propagation acoustic delay between the detector and actuator unit in a waveguide
ω	angular frequency $2\pi f$, where f is frequency

1. Introduction

Active control of sound refers to systems in which controllable sources of sound (secondary sources) are used to modify an existing sound field to a desired one. If the control is applied especially to reduce noise, one talks about active noise control or cancellation (ANC), active noise reduction, or active noise absorption (ANA). Active noise reduction may be based, e.g., on active absorption, active back-reflection (ABR), or local or global active potential energy minimization.

Constructive interference is a phenomenon where a signal is amplified by another signal. On the contrary, in destructive interference the signals cancel each other to some degree. The nature of the interference depends on the phase relationships of the signals: signals with equal phases add constructively and signals with opposite phases destructively. Figure 1 shows the sum signal of two identical signals with different mutual phase shifts.
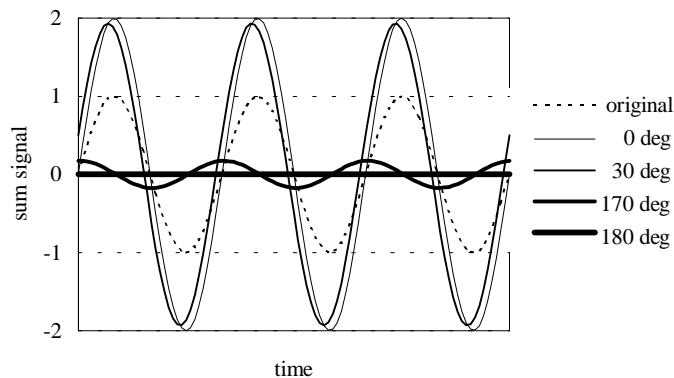
Figure 1. Sum signal of two identical signals with a mutual phase shift between 0 and 180 degrees.

1.1 First steps in active control of sound

The idea for active noise reduction is quite old. The first patent for it was granted to Lueg in 1936 [1]. The idea of the patent was to produce an acoustic wave interfering destructively with the wave to be reduced. The patent dealt

with one-dimensional sound in a duct and sound in a three-dimensional space. In the *duct system*, a detector microphone was set at a proper distance from the loudspeaker upstream so that the sign of the sound originating from the microphone-amplifier-loudspeaker chain was opposite to that of the primary sound at the loudspeaker location. The time delay between the signals as an acoustic propagation delay corresponded to a distance of an odd multiple of half the wavelength of sound. It can be easily seen that this kind of construction works well only for sinusoidal sounds at certain frequencies. In the *three-dimensional system*, the sound was cancelled locally near the loudspeaker. The local functioning was due to the fact that proper phase relationships could be obtained only in a limited region when using one loudspeaker. The technology level of the electronics was not high enough in the 1930's to construct control systems accurate enough for Lueg's systems to work properly [2].

In 1953, Olson and May published a principle of an electronic sound absorber [3]. More detailed aspects and possible applications were given in 1956 [4]. Besides that the device can be used to absorb sound impinging on the microphone, it can create a "zone of silence" in front of it by a proper phase difference between the incoming and radiated sound. This idea is quite similar to the three-dimensional system of Lueg. The technology level of the 1950's made it possible to adjust the phase with a reasonable degree of accuracy over a frequency range adequately wide [2]. Many non-idealities limited, however, the practical frequency range to about two and one-half octaves. The spatial range of the system was quite small (about thirty centimetres).

In 1955, Conover and Ringlee [5] and Conover [6] presented an active noise control system for a transformer. The system was patented and implemented. The loudspeaker was placed near the surface of the transformer in order to locally reduce the transformer noise in the near-field. Because of using only one loudspeaker, the destructive interference occured only in certain directions; in fact, the constructive interference amplified the noise in other directions. Since Conover's experiments, the active noise control of transformers has been investigated widely [7–9]. One of the main reasons for this is the periodicity of the low-frequency content of the noise, which facilitates the active control in a great amount.

Lueg's patent did not result in any applications in the 1930's and 1940's. Olson and Conover stimulated interest in ANC but, nevertheless, the interest ceased at the turn of the 1950's and 1960's [2].

1.2 Beginning of a new era in active control of sound

From the late 1960's, the interest in active control of sound began to grow substantially. This was made possible by the development of control systems (especially autonomous systems) and electronics, and by the improved understanding of the behaviour of acoustic fields [2].

Jessel and his co-workers in France had investigated active control of noise from the late 1960's onwards. This will be examined in more detail in Section 1.4. Kido and his co-workers in Japan began to work with the active attenuation of transformer noise in the late 1960's [7–9]. Some researchers in the Soviet Union began to work with ANC in the early 1970's in the wake of Malyuzhinets. This will be examined in more detail in Section 1.5.

Jessel and Kido stated that active control systems for sound work better at low frequencies [2]. This can be seen to be a benefit in the sense that traditional passive devices for transmission loss and silencing are very large if high efficiency at low frequencies is needed. Later in 1982, Warnaka proposed that hybrid systems where low-frequency noise (below about 500 Hz) is attenuated actively and high-frequency noise passively would be advantageous [2].

The general history of the active control of sound has been presented here till the beginning of the development of the JMC method and the Malyuzhinets' method, and it will not be examined further. Section 1.4 of Introduction deals with the history of the JMC method and Section 1.5 that of the Malyuzhinets' method.

Nowadays control systems for ANC are typically implemented with a digital signal processor using adaptive filters implemented often with the LMS (least mean square) algorithm [101–103], especially the filtered-x LMS algorithm, developed in 1981 [104–106], and the multiple-channel version of it [107]. Introducing the first single-chip digital signal processors in the early 1980's fa-

cilitated a great advance in digital signal processing techniques [108]. However, it was not until the 1990's that the development in digital signal processing made it possible to construct practical commercial control systems for ANC [109], and the progress in microelectronics providing VLSI (very large scale integrated) circuits made it possible to use adaptive control in real-time applications [63]. Canévet stated in 1978 that the actual problem in ANC is in realizing pertinent actuators with suitable acoustic properties [36]. This is a real problem also at the time being. It is believed that, e.g., flat film actuators may solve some practical problems in this sense **[II]**.

1.3 Basic approaches for active control of sound

There are two basic approaches for active control of sound. One could be called the *facility-based approach*. The other might be called the *problem-oriented approach*.

In the *facility-based approach* the starting point are all the available facilities, including different signal processing methods and algorithms, hardware, and peripheral equipment such as sound detectors and actuators. Typically in that approach, the first step is to select some signal processing method and algorithm, suitable hardware, and sometimes even the configuration of the detectors (reference and error inputs) and actuators (secondary sources). Then it is estimated what can be done with this kind of configuration. After that the configuration is varied, to find some optimal system for a defined problem. The acoustical field-theoretical aspects may be taken into account to some extent (e.g., in tracing reasons for non-functioning), but they seldom affect the selection process.

One drawback of this approach is that the first selections of the configuration limit the efficiency of the system so that a true optimal solution for a given problem will probably not be achieved; it is possible to obtain the optimum only in the subspace spanned by the selected configuration principles. It can be said that the limitations in this approach are of first order, because the fundamental limiting factors are already at the first stage of the procedure. As another severe drawback, this approach may lead to erroneous conclusions in deducing general

properties of systems for active control of sound. Some examples of this are given in the Introduction of **Publication [II]**.

In the *problem-oriented approach*, the desired goal of the problem is first defined. The principal question after that is what kind of a system configuration is needed to achieve the desired goal. After solving this, the optimal configuration is approximated by some realizable configuration as exactly as necessary. The signal processing system, detector and actuator types and configurations, and the possible criterion for the adaptive process are thus defined on the basis of the desired goal and the acoustical field-theoretical relations. Lastly, the limitations and effects of the approximations in the practical realization are evaluated. This approach requires systematic field-theoretic tools in solving the principal question.

An essential feature of this kind of a systematic tool is the possibility to obtain an exact solution to the problem. The approximations are due to the practical realization of the exact solution. All limitations of the system in this approach arise from the approximations of the ideal system, not from the basic configuration itself, so the limitations form only an effect of second order. As a consequence, the solution will be an approximation of the optimal solution at the best level of acceptance, the deviations from the optimum being of second order. Also erroneous conclusions in deducing general properties of systems for active control of sound can be avoided because the true optimal solution is known.

There are not too many systematic tools utilized in the active control of sound. Besides the JMC method and its expansions, see Section 1.4, there is the Malyuzhinets' method, see Section 1.5, which can be defined as a simplified special case of the JMC method. The theory of distributions or the optimal methods used by Gaudefroy [110, 111] can be categorized to systematic tools, but they are beyond the scope of this thesis. According to Mangiante, the theory of distributions is much less general than the JMC method [57].

This work concentrates only on the problem-oriented approach in ANC, and especially on the JMC method.

1.4 History of the JMC method

The history of the JMC method, presented here, is based on references [10] – [74] and **Publications [I]** – **[VI]**. The theory of the JMC method itself will be presented here only in such a degree that the development of the JMC method is easy to understand. In this thesis, the basic theory is found in **Publication [II]**, and in a briefer form also in **Publications [I]** and **[III]**.

The JMC method is suitable for formulating the problem of active noise control with the general system theory. Furthermore, the method can be more generally applied to reshaping of acoustic or any other fields [17, 31, 40, 45, 47, 49, 50], to wave reconstruction (holochory, holophony) [17, 44, 50, 52, 57], and to wave propagation problems [38, 68, 74]. Its name originates from the first three pioneers of the method: **J**essel, **M**angiante, and **C**anévet [45] (the JMC group). A generalized JMC method has been proposed by Mangiante [53, 55], and a modified JMC method has been introduced by Uosukainen [54, 64, **I**–**III**]. In principle, whatever the primary sound field is, it can be changed (reshaped) into any other field by using the JMC method. So it forms a general theoretical approach for the active control of sound.

It has been depicted that, due to the need of continuous monopole and dipole secondary source surfaces (or zones), the applicability of the JMC method in practical constructions is questionable for the time being, see, e.g., [102]. Opinions of this kind often ignore that the JMC method and methods related to it can be applied also to partial surfaces or point sources [30, 59–61, 65–67, 79]. Furthermore, in using JMC sources instead of conventional ones, the signal processing and the adaptive control systems can be much simpler, which in turn reduces the computing time and improves the efficiency of the system [53, 56, 63]. The simplification of the algorithms is based, e.g., on the absence of backward radiation of secondary sources in the JMC method: in the ideal case there is no acoustic feedback to the detectors. This enhances the stability by increasing the phase and gain margins of the system [56].

1.4.1 Background of the development of the JMC method

The Huygens' principle states that the field of a source can be defined without any knowledge of the source itself if we know the field on a closed surface

around the source, see, e.g., [112]. The field on that surface acts as a secondary source distribution to the field outside it. The secondary source distribution causes no field inside the surface. The field of the secondary source distribution is mostly calculated by using a surface integral, the Helmholtz-Huygens' integral, see, e.g., [113], over the secondary source distribution.

As early as 1954, Jessel presented the Huygens' principle using the operator presentation, instead of relying on Green's identities presented by the surface integral [10] (reprinted in more detail in, e.g., [17]). The principle was formulated to any fields obeying linear differential equations. The volume is decomposed to three zones with a "cutting-out operator" (the term was not in use at that time): one having the primary sources whose radiation is replaced with that of Huygens' secondary sources, one containing the secondary sources, and one where the secondary sources give the same field as the replaced sources, see Figure 2. The secondary source zone should isolate the two other zones from each other (i.e., one of them shall be enclosed by the secondary source zone, or the secondary source zone shall be infinite in two dimensions). The density of Huygens' secondary sources is obtained as a commutator of two operators acting on the primary field quantities. When the secondary source zone is a simple surface, one obtains the same formulae of Huygens' sources as with the traditional Helmholtz-Huygens' integral [51] (some extra specifications to this will be given later).

Jessel noticed that there exists a set of configurations related to the Huygens' principle which forms a complementary entity (the sum of the secondary sources of the whole set is zero, the total effect of all the "cutting-out" operators being an identity operator) [10]. In 1966, Jessel gave formulae for the Huygens' principle applied to linear acoustics [11]. In that context he introduced a complementary entity of two separate "cutting-out" operations, one of which being the Huygens' principle and the complementary one leading later to the JMC theory of active absorption, see Figure 3. Based on this idea of complementary decomposing in acoustics, the JMC group started its work in 1967 at CNRS Laboratories in Marseilles, the group consisting of Jessel, Mangiante, Canévet and some co-workers [46]. The group worked about thirteen years [61], obtaining the formulation of the JMC method and making many experiments based on it.

zone 1: contains primary sources (PS), to be "cut out" to zero (M = 0)
zone 2: contains secondary sources (SS) (0 < M < 1)
zone 3: field remains original (M = 1) if primary sources are replaced with secondary ones
M: weight operator of Huygens' principle

case a: primary source zone enclosed by secondary sources
case b: unaltered zone enclosed by secondary sources
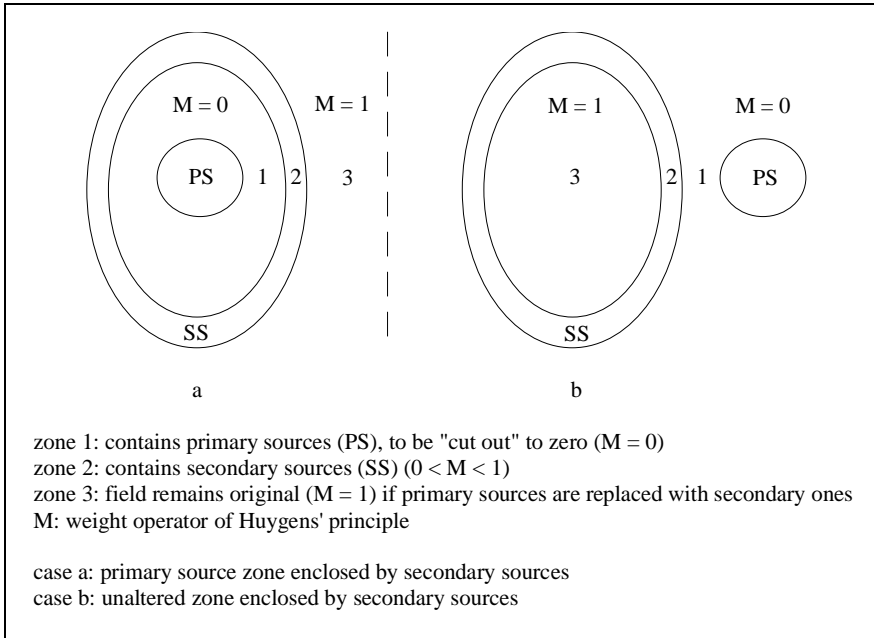
Figure 2. The various zones in the Huygens' principle.

zone 1: contains primary sources (PS), not to be altered (M = 1)
zone 2: contains secondary sources (SS) (0 < M < 1)
zone 3: field suppressed to zero (M = 0) by secondary sources
M: weight operator of the active absorption

case a: primary source zone enclosed by secondary sources
case b: silenced zone enclosed by secondary sources
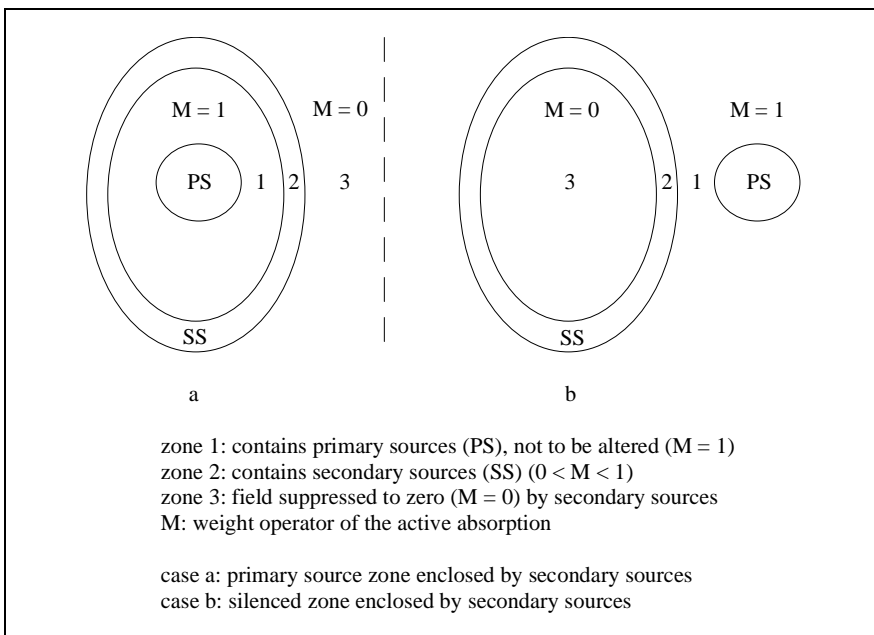
Figure 3. The various zones in active absorption.

Since 1980, Jessel, Mangiante and their co-workers, and some other people, have worked, based on the JMC method, with wave propagation, active sound absorption, general system theory, holophony [61] and field reshaping [46]. According to them, the "designer's equation", arising from the field reshaping theory, can be considered as the most general approach to active control of sound [46, 48, 55].

1.4.2 Development of the terminology

The active absorption method, based on the Huygens' principle, was first called the JMC method by Jessel in 1983 [45].

The *perturbation operator* used in the JMC method for field reshaping was called (especially in the cases of the Huygens' principle and the principle of active absorption) a "cutting-out" operator in 1972 by Jessel and Mangiante [15], an "adjustment operator" in 1979 by Jessel [37], a "weight operator" in 1981 by Jessel [41], a "modification operator" in 1983 by Jessel [45], a "modifier" in 1985 by Jessel [46], a "reshaper" in 1988 by Jessel [49], "reshaping operator" in 1991 by Jessel [58] and a "field reshaping operator" in 1993 by Mangiante [63]. The term "field reshaping", meaning any arbitrary modification of the primary field, was adopted by Jessel as early as 1985 [46]. The perturbation operator, when used as a simple *perturbation function*, was called a "weight function" in 1972 by Jessel and Mangiante [15], a "weighting factor" or (especially in the cases of the Huygens' principle and the principle of active absorption) a "cutting-out function" in 1976 by Jessel [25], and a "modifying function" in 1988 by Illényi and Jessel [50]. The terms *weight operator* or *weighting (function)* will be used in this thesis.

The equation for the secondary sources, originating from the formulation of the JMC method, was called the "commutator formula" by Jessel in 1983 [45], the "designer's equation" in 1985 [46] and the "designer's formula" in 1988 [49].

In 1975, Canévet introduced the term *tripole* ("tripolaire" in French) to mean a secondary source element consisting of a monopole and a dipole [24]. In that text and in many papers after it, it can be deduced that the source components of the tripole have a common input signal (single input), probably weighted differently, see especially [43] and [48]. However, in a paper by Mangiante,

Mathevon and Roure in 1997 [73], the name tripole is used in the two-input case where the monopole actuator is fed by a dipole detector and the dipole actuator by the monopole detector, and this configuration is the general JMC source without a quadripole element [67]. This practice will be adopted in this thesis, and a tripole with a common input signal for both actuator types will be called a *single-in tripole*. This term has not been used in the literature.

Besides the monopole and dipole sources, the third type of secondary source needed in the JMC method was called a "rotation-source" by Jessel in 1979 [37], a "quadripole" or "vortex" by Jessel and Angevine in 1980 [40], and a "torque-source" by Jessel in 1988 [49]. The term *quadripole* will be used in this thesis. The secondary sources as a whole were called "JMC sources" by Jessel in 1985 [46].

Jessel formulated different cases of active absorption in 1981 so that the secondary source zone around primary sources is called an "active screen", around the space to be silenced an "active shield", and a secondary source zone (or surface) not forming a closed surface an "active barrier" [41].

1.4.3 Development of the JMC theory

In acoustic fields the first order field quantities to be treated are the sound pressure and the particle velocity. Jessel presented the idea of active absorption and the *secondary sources needed* for acoustic fields in flowless, homogeneous ideal fluids based on a complementary configuration of his formulation for the Huygens' principle in 1968 [12], leading to the need of three types of secondary sources: *monopole, dipole and quadripole distributions*. The traditional Helmholtz-Huygens' integral only needs monopole and dipole distributions. A separate presentation was given for planar surface secondary source distributions. The *reference signals* for the secondary sources are obtained from the *primary sound pressure and particle velocity*. The secondary sources (and the reference detectors they need) are assumed to be *acoustically transparent*. The expressions for secondary sources were reprinted by the JMC group in, e.g., [14–19, 26, 29, 31, 37, 40–42, 46, 48–50, 52, 55, 57, 60, 66, 69]. The quadripole sources are included in some of the presentations. The function of the quadripole sources is to enable the transversal discontinuity in the particle velocity, the discontinuity originating from the field weighting factor [15]. Concerning the

field radiated by the secondary sources, the effect of the quadripole distribution is to tilt the vector field produced by the dipole distribution [37]. Jessel and Mangiante generalized the presentation of the secondary sources to include the effects of internal losses and a flow of the medium in 1972 [15] (reprinted in [17] and [42]). In 1974, Mangiante presented the same equations with the stress tensor given by the help of viscosity coefficients [22] (reprinted in [28] and [69]).

Mangiante presented in 1968 that in *one-dimensional fields* (in waveguides with only a plane wave propagating) the single-in tripole source configuration, having a cardioidic radiation pattern, produces the right source outputs (as Huygens' sources) [13] (the term "tripole" was not used in that paper). The secondary quadripole sources are not needed in the one-dimensional field. Mangiante presented in 1973 [18] how a radiator with a cardioidic radiation pattern is valid also in a three-dimensional space if the secondary sources are far enough from the primary sources so that the primary field can be considered a spherical wave at the location of the secondary sources [29]. Canévet and Mangiante demonstrated in 1974 in an illustrative manner how the monopole-dipole combination in the waveguide has unidirectional properties (no sound upstream) and how the anti-sound pressure downstream is half due to the monopole and half due to the dipole radiation [19, 22] (reprinted in [28]). The presentation of the secondary sources in one-dimensional fields was further extended to take a steady flow into account by Jessel and Mangiante in 1972 [15] (reprinted in [20]).

In 1972, Jessel and Mangiante formulated the *operator presentation* of the principle of the active absorption by Huygens' sources in a more general way with the help of Jessel's general perturbation lemma [15]. The aim was capability of handling also more complex field-reshaping problems (the term "reshaping" was not introduced in that presentation). The sum of the weighting factors of the Huygens' principle and the principle of active absorption was seen to be equal to one (the weighting factors forming a Urysohnian couple), and the secondary sources of the active absorption was seen to be that of the Huygens' principle with the sign reversed (complementarity of the principles). In 1976, Jessel presented that the operator for field equations does not need to be linear in principle, the linearity is supposed only for the complementarity of the Huygens' principle and the principle of active absorption [25]. In 1977, Jessel divided the

operator for field equations to a linear and a non-linear part [35]. The operator presentation was given in 1979 in more detail by Jessel [37]. In that paper, a general theorem was given for dividing a field into a couple of complementary fields, by first dividing the space into two complementary fuzzy parts. One special case of that theorem was the complementary couple of the Huygens' principle and the principle of active absorption. In 1981, Jessel introduced different weight operators for the field and the source quantities [41]. The diffraction effects were taken into account by Jessel in 1988 [49]. The operator presentation of the active absorption was reprinted by the JMC group, e.g., in [17, 22, 25, 28, 31, 45–49, 53, 55, 56, 58, 66, 74], in the non-linear case in [69], with the idea of different weight operators in [57, 61, 69], and with diffraction effects in [57, 69].

In 1973, Jessel presented the *generalized Huygens' principle* in which only a part of the primary sources was replaced with the secondary ones, primary sources existing thus also in zone 3 of Figure 2 [17] (reprinted in [69]). Furthermore, Jessel presented the *very generalized Huygens' theorem* in 1991 [58]. In this theorem, the secondary sources can lie in different (not connected and not intersecting) zones, some of them possibly reduced to quasi-geometrical points. By using the very generalized Huygens' theorem for active absorption, it is possible to introduce separate secondary source zones for separate primary source regions or point sources, or for separate zones to be silenced.

Jessel extended the wave decomposing method by applying it to *holophony* (reproduction or reconstruction of an acoustic field, acoustical counterpart of holography) in 1973 [17]. Illényi and Jessel discussed its generalization *holochory* which can be applied to any fields, in 1983 [44], and in more detail in 1988–1989 [50, 52]. Mangiante stated in 1991 that the JMC method offers a definite approach to holochory [57]: with it an arbitrary physical field may be exactly *reconstructed* (the Huygens' principle, holophony), a given field may be arbitrarily *remodeled* (active absorption), and even *diffraction*, *refraction* and non-linearities can be taken into account.

Canévet proposed to use Jessel's decomposing method to solve acoustic *propagation problems* in inhomogeneous transition layers and in waveguides with a changing cross-section in 1980 [38]. The space is divided into Urysohnian subspaces so that the propagation problem can be solved in an easier way separately

in the subspaces. In numerical simulation of wave propagation problems it is often essential to define synthetic boundaries to reject the space in the computation and to eliminate the reflections from these boundaries so that a free space solution for the problem is approximated [114]. In 1994, Charles, Kapotas and Phadke presented the idea of using Huygens' sources according to the JMC method to obtain absorbing boundary conditions [68] (reprinted in [74]).

In 1983, the JMC method (it was called so since then) was attached to the *general system theory* by Jessel [45]. General system theory leads to procedures where instead of deducing the response (effect) on the basis of a given excitation (cause) one tries to define the excitation that produces a given response. The JMC method can be seen to be based on the "anticausal analysis", because a wanted field is taken as a starting point and after that proper sources (causes of the field) producing it will be defined [46]. Resconi and Jessel introduced a *general system logical theory* in 1986 [47]. It was a combination of Resconi's logical theory of systems and Jessel's theory of secondary sources. With the help of the theory the JMC method was assigned to a more general framework. In that framework many field-theoretical problems, besides the Huygens' principle and the principle of field-reshaping, may be approached, e.g., also scattering problems. The theory can be applied also to other than field-theoretical problems, geometries and chemical controls being given by Resconi and Jessel as two application areas. The general system logical theory can be applied to complex problems, due to its ability to deal with networks of elementary logical systems. The author is not aware of any applications of the JMC method thus extended to networks of systems up to now. The JMC method was briefly presented in the light of the general system logical theory also in [57].

In 1988–1989, Illényi and Jessel proposed a system of processing the wanted and unwanted signal differently by choosing *different reshaping operators* to the components of the signal [50, 52]. If the separate processing happens in the same part of space, one needs selective processing of the signal, utilizing physical discrimination (the differences in the signal components are utilized) or non-physical discrimination (based, e.g., on psychoacoustical criteria).

Mangiante introduced the *generalized JMC method* in 1989–1990 [53, 55]. In the generalized JMC method, it is possible to define various boundary conditions at the boundaries of the secondary source zone, by using different kinds of

source types (monopoles, dipoles, tripoles) on concentric surfaces or between them in the secondary source zone. This enables one to define many existing source configurations used in ANC, so they may be categorized as special cases of the generalized JMC method.

Uosukainen presented the *modified JMC method* in 1989–1990 [54, **I**] (reprinted in [57, 64, **II**, **III**]). The modified JMC method differs from the original one so that in the former the primary sources are not changed in any case. The *vector* and *dyadic weighting* factors were defined by Uosukainen through the modified JMC method, to get possibilities to reshape individual field quantities independently. Mangiante presented the vector and dyadic weightings for the original JMC method in 1991 [57], and further, Mangiante and Roure presented them in more detail in 1994 [66].

1.4.4 Constructions and control systems of the JMC elements

A schematic presentation of a *JMC element*, i.e., a detector-actuator combination according to the JMC method, was given by Jessel in 1972 [16]. Mangiante gave a theoretical block diagram of an active noise absorber in 1973, based on the single-in tripole approximation of Huygens' sources [18] (reprinted in [22, 29, 31]). In 1994, Mangiante and Roure presented the same based on a combination of a tripole detector and a tripole actuator [66, 67]. Jessel and Angevine stated in 1980 that the monopole and dipole radiation can be realized with two loudspeakers with proper phase relationships of their input signals [40]. Jessel stated in 1988 that particle velocity (dipole) detectors may often be replaced successfully by sound pressure (monopole) detectors [49]. Also he warned that the same logic in the actuators may cause problems: replacing the force sources (dipoles) with volume velocity sources (monopoles) changes the absorptive system into a reflective system, causing acoustic feedback to the reference signal. Uosukainen presented in 1998 four three-unit approximations of a JMC element, composed of either two detectors and one actuator, or one detector and two actuators **[III]**.

Basic block diagrams applied to *waveguides* have been presented by the JMC group for single-in tripoles, e.g., in [15, 36, 48], and for a combination of a tripole detector and a tripole actuator, e.g., in [42, 43]. A block diagram of a JMC control system was presented by Mangiante in 1990 [56], and in greater detail

by Mangiante, Mathevon and Roure in 1997 for a construction having a tripole detector and a tripole actuator especially for waveguides [73]. In 1995–1996, Uosukainen presented the structure of ideal three- and two-element unidirectional actuators (based on single-in tripoles) to be applied to one-dimensional waveguides [70, 71]. Many approximate sub-optimal solutions were also given. In 1997–1999, Uosukainen and Välimäki extended the number of optimal and sub-optimal two-element solutions by introducing different inter-channel delays [72, **IV, V**]. In 1998, adaptive signal processing structures for the two-element ideal solution were given by Välimäki and Uosukainen **[VI]**. Mangiante, Mathevon and Roure presented a tripole construction for a self-directional secondary source in a duct in 1997 [73], where the delays needed between the monopole and dipole parts are realized by a particular placement of the microphones and secondary sources; no electronic controller is needed for them.

1.4.5 Effects of inaccuracies and approximations

In 1973–1975, Mangiante studied the effects of amplitude and phase errors of the secondary sources on the efficiency of the system [18, 21–23]. He found in that construction that to obtain an attenuation of 40 dB for pure tones, the amplitude error has to be less than 0.04 dB and the phase error less than 0.01 rad. The results were reprinted in [28] and [29].

In 1973–1974, Mangiante studied the effects of discontinuous secondary sources on the efficiency of the system for pure tones [18, 22]. In 1977, with the help of simulation Mangiante and Vian showed that the validity of the Huygens' principle and thus the principle of active absorption via a closed surface was retained with a finite number of secondary sources [30]. A criterion for the number of secondary sources was given, see also [31]. Jessel and Angevine noticed by simulation in 1980 [40] that attenuation increases when the number of secondary sources increases, but only up to an optimal number of actuators. In 1992–1993, Mangiante presented numerical simulations of discontinuous density of secondary sources on a closed surface of the form of a prolate spheroid [60, 61]. He found that due to the discontinuity there is minor risk of acoustic feedback, and that significant attenuation of the primary field can be obtained everywhere in the space to be silenced and not only in a few points. When active sound absorption is applied to large spaces, from a practical point of view the total number of secondary sources may become too high at high

frequencies. According to Mangiante [61], this is not due to the JMC method but rather it is an evident consequence of Shannon's sampling theorem (one must have at least two samples per wavelength to avoid aliasing).

1.4.6 Experiments

Experiments in *ducts* have been made by the JMC group beginning from 1967 up to now [13–15, 19, 20, 22, 24, 27, 36, 37, 43, 73]. Single-in tripoles have been used in all experiments except one [73]. Frequency ranges have been between 70 Hz and 1200 Hz; in one experiment with a pure tone frequency up to 8 kHz [19]. A typical attenuation for pure tones was 50 dB; up to 75 dB at best [20]. A typical attenuation for pure tones with flow present (6 m/s) was 45 dB [36]. With broad-band noise a typical attenuation was 25 dB [27], and with flow present (6 m/s, 12 m/s) 10 dB [36, 43]. According to Canévet [36], the main difficulty with broad-band noise was that the frequency responses of a monopole and a dipole are generally different, and their relative phase and amplitude equalization in a broad band is difficult to realize. A standing wave ripple upstream (due to upstream radiation of the secondary sources) was typically less than 1 dB [15, 19].

Experiments in a *three-dimensional space* have been made by the JMC group [22, 31, 40, 62, 67] and by Hasebe *et al*. [59, 65], using sources constructed of single-in tripoles [22, 31, 40, 59, 65] or tripoles [67]. Frequency ranges have been between 100 Hz and 1500 Hz. Experiments have been made with (discontinuous approximations of) closed secondary source surfaces [22, 31, 40, 62] and with (discontinuous approximations of) partial active barriers [59, 65, 67]. A typical attenuation was 25 dB, both for pure tones [31, 67] and for wide band noise [65]. The primary field was not modified in the uncontrolled zone (zone containing the reference microphone and primary source) [31, 67] but, however, it increased near the secondary sources [67]. With partial active barriers the sound pressure level was substantially reduced in a large sector around the error microphones [65, 67]. Thus, with a good approximation, the tripole secondary sources had Huygens' directivity characteristics [67]. No knowledge of the propagation direction of the primary field was needed [67]. Similar results to those of the experiments in [67] have been obtained with simulations in [66].

1.5 History of Malyuzhinets' method

The development of the Malyuzhinets' method is presented here on the basis of references [75] – [100], written by scientists in the Soviet Union. In fact, the Malyuzhinets' method can be categorized as a special case of the JMC method. So the categorization to the development of the Malyuzhinets' method is here done merely on a geographical basis: it is the development of the problem-oriented approach of ANC in the Soviet Union.

1.5.1 Development of the theory

Independently of Jessel and his co-workers, Malyuzhinets developed a method for the active control of sound in 1971 in the Soviet Union [75]. According to Jessel, the Malyuzhinets' method can be used only with waves obeying Helmholtz' or d'Alembert's equations [25, 45], so its field of application is not as general as with the JMC method.

In the Malyuzhinets' method, usually two concentric closed Huygens' surfaces are specified; one for the detectors and one for the actuators. Monopole and dipole transducers are needed on both surfaces. The input signals for the actuator surface are calculated from the output signals of the detector surface. Because the detector and actuator surfaces are apart from each other, the whole detector surface has an effect on every point of the actuator surface. When the detectors and actuators are discretized, the actuators are controlled by a MIMO (multiple input – multiple output) system: every detector element affects every actuator element [77]. With the formulation of Malyuzhinets, both the field inside the actuator surface and the field outside the surface may be suppressed simultaneously. So in a general case two detector surfaces are needed, the actuator surface being between them. In the original formulation of the method, also the scattered field due to scattering bodies inside the actuator surface may be suppressed outside the surface. As in the JMC method, the detectors and the actuators are assumed to be acoustically transparent.

The Malyuzhinets' method uses detector and actuator surfaces. In the JMC method, also zones can be used. In Malyuzhinets' formulation, no quadripole sources are present.

In 1975, Fedoryuk formulated the Malyuzhinets' method especially for *waveguides* [78]. Generally, the Malyuzhinets' method has been mostly applied to waveguides, for single mode cases [76, 83], for two-mode cases [87, 96], and for multi-modal cases [84, 85, 89, 92].

Fedoryuk used the *operator presentation* in the formulation of the acoustic field equations in 1976 [82]. He included the possibility of variable density and velocity of sound in the noise cancellation formulation. The formulation is done in the time domain, to make it possible to handle nonsteady problems.

Fedoryuk introduced in 1979 the possibility of using *two monopole surfaces* instead of using one surface with monopole and dipole distributions [90], both for detector and actuator surfaces. He noticed that the physical distance between the surfaces induces an upper frequency limit, the distance corresponding to half the wavelength at that frequency. This configuration can be regarded as a three-dimensional generalization of the two-element Swinbanks' source in a waveguide [139]. When applied to a single-mode waveguide, as done by Mazanikov and Tyutekin already in 1976 [83], it results to the two-element Swinbanks' configuration (both the detector and the actuator). The principle was applied to a waveguide with two modes in 1977 by Mazanikov *et al*. [84, 87].

Konyaev, Lebedev and Fedoryuk specialized the two monopole surfaces as two concentric spherical surfaces with discrete detectors in 1979 to determine the spherical harmonics of a sound field [91]. Mazanikov, Tyutekin and Fedoryuk continued that work in 1980 including monopole actuators, besides detectors, distributed on concentric spherical surfaces [94], the acoustic field being expanded in spatial harmonics. The field expansion makes it possible to simplify considerably the signal processing. Further, Korotaev and Mazanikov studied the sound cancellation by a finite planar array of monopole and dipole transducers in 1985 [97]. They stated that the number of connections in the MIMO control system can be decreased considerably by presenting the field with spatial harmonics (e.g., modes of a waveguide).

1.5.2 Approximations

Zavadskaya, Popov and • gel'skii studied the effects of discretation of Huygens' surfaces on the efficiency of the Malyuzhinets' method in 1975 [79, 80]. They concluded that the discretized secondary source distribution can be made as precise as necessary and feedback can be suppressed by choosing the number of discrete actuators large enough. Further, they concluded that the approximation is the better the farther the observation point is from the surface. Also, they showed that Huygens' source surface works even if it is not totally closed, making shadow zones in that case. In 1977, they argued that to avoid acoustic feedback, the maximum distance between near-by actuator elements should be a little smaller than half the wavelength [86]. Konyaev, Lebedev and Fedoryuk gave a criterion for the "wave density" of an array of radiators on a surface in 1977 [88].

As an approximation of Malyuzhinets' solution, Urusovskii introduced a configuration with a monopole actuator and a dipole detector on the same cross section of a waveguide in 1980 [92]. He noticed that the system works because the monopole actuator does not have any effect on the dipole detector on the same plane. The same basic idea with two monopoles at each side of a dipole has been introduced to cancel the field beyond a slit in a rigid baffle by Zavadskaya, Popov and • gel'skii in 1980 [93].

As further approximations, Urusovskii examined in 1981 three specific problems in the active sound cancellation by monopoles on a single surface controlled by sound pressure and radial particle velocity detectors on concentric surfaces [95]. Ivanov used monopole actuators with detectors formed by two concentric monopole surfaces in the active cancellation of the diffracted field of a slit in a baffle in 1987 [99].

1.5.3 Experiments

A few experiments on the efficiency of the Malyuzhinets' method are available, all of them made by Mazanikov, Tyutekin, Ukolov and Klimov [76, 83, 87, 96]. They all concern waveguides filled with liquid, so the typical frequency ranges, being between 5 kHz and 15 kHz (one experiment below 4.5 kHz [83]), are higher than in the experiments of the JMC method. A typical attenuation at dis-

crete frequencies in a single-mode waveguide was about 25 dB [76, 83], and with wide band noise in a single- or two-mode waveguide about 15–20 dB [83, 87, 96].

The acoustic feedback from the actuators to the detectors was typically less than –40 dB, the primary field remaining practically unchanged upstream from the actuators [76].

1.5.4 Some aspects of the method

Zavadskaya, Popov and • gel'skii stated in 1975 that errors in the control system grow boundlessly if the detector and actuator surfaces approach each other [79]. Further, Konyaev and Fedoryuk stated in 1987 that approximation errors due to discretization of the detector and actuator surfaces increase if those surfaces approach each other [100]. On the contrary, in the JMC theory, concerning especially the duct applications, Jessel emphasized in 1981 that the reference detectors should be located near the actuators [42]. For more general cases, Jessel emphasized in 1988 the tight-coupling [49] which can be understood so that the detector signals for the actuator elements have to be picked up quite near the actuators. This difference of opinions is probably due to the fact that in the Malyuzhinets' method the primary field quantities on the actuator surface are calculated from the measured field quantities on the detector surface by using the Helmholtz-Huygens' integral with appropriate Green's functions. This integral presentation is singular in points where the detector and actuator surfaces coincide. On the other hand, if the detector signal is measured just before the actuator surface, as it is recommended in the JMC method, the actuator output is defined solely by the field quantities locally just at the actuator, and there is no integration with singularity. In the discretized case, the MIMO system of the Malyuzhinets' method is thus converted into a multiple SISO (single input – single output) system in the JMC method.

A general feature in the history of the Malyuzhinets' method is that the method itself has not been developed much after its publication by Malyuzhinets. General rules for solving different field reshaping problems have not been given. Essentially, the method gives the proper actuator and detector types to be used.

1.6 Purpose of this thesis

The JMC method is the most powerful problem-oriented approach in the active control of sound. It forms a general theoretical approach for ANC. In this thesis, the theory of the JMC method is extended and new source configurations based on the JMC method are developed. The results of this work enlarge the possibilities in ANC and facilitate more useful applications to be realized in ducts and three-dimensional spaces.

This work can be divided into development of three issues:

1)   the modified JMC method, and vector and dyadic weightings for it
2)   the principles of three-unit approximations of a planar JMC element
3)   new JMC source configurations for waveguides (duct applications).

Background and contribution to these issues are briefly described in the following sections.

This thesis is based on theoretical examination, no experimental work is included. Applications of the modified JMC method and the new weightings are presented in quite a general level. Practical problems in realizing the new source configurations are not treated. Simulations have been done in connection with the source configurations for waveguides.

1.6.1 Modified JMC method

In the facility-based approach, the easiest way for active noise reduction in practice is to have one or several "anti-noise" actuators as secondary sources, which cause, together with the primary sources, interference minima to selected points or local regions (local active potential energy minimization). If there are enough anti-noise sources and detection points, it is possible to minimize the potential energy of a closed system in this way (global active potential energy minimization). The global minimization of the potential energy is normally based on the modal approach (minimization mode by mode). The local control is best realized in the near field of the secondary source (using the principle of the acoustic virtual earth). The secondary sources can also be optimized to maximize the acoustic energy they absorb (active noise absorption) or reflect back-

wards (active noise back-reflection). A literature survey of these various ways for noise reduction and about the various ways of optimizing the secondary sources, compared to the problem-oriented JMC method, is given in the Introduction of **Publication [II]**, see also, e.g., [102, 115–124].

In the JMC method, the weight operator affects, besides the field quantities, the primary source strengths as well. The JMC method is mostly applied by using the scalar-weighting factor in which all the first-order field and source quantities are weighted similarly. In 1981, Jessel introduced different weight operators for the field and source quantities [41].

In this work, a modified JMC method is developed. The difference between the JMC method and the modified version of it is that in the latter the primary sources remain unchanged in all cases. This is advantageous because in practical situations we have restricted possibilities of weighting the primary sources in any way. On the basis of the modified JMC method, as new concepts, the vector and dyadic weighting factors are defined. These give more degrees of freedom for field reshaping. Possibilities of general field modifications and optimization of secondary sources, based on the scalar, vector and dyadic weighting factors, are given.

Mangiante presented the vector and dyadic weightings for the original JMC method in 1991 [57], and further, Mangiante and Roure presented them in more detail in 1994 [66].

1.6.2 Planar JMC element and its three-unit approximations

Jessel introduced a schematic presentation of a general JMC element in 1972 [16]. Mangiante and Roure gave a theoretical block diagram of a combination of a tripole detector and a tripole actuator for three-dimensional applications in 1994 [67]. A detailed description of the various parts of the JMC element lacks in the literature.

Such solutions where some part of the JMC element is omitted and its function is compensated by some optimization method have not been presented in the literature. The single-in tripole [13, 18], including the assumption of a plane or spherical wave as the primary field, however, can be categorized as a simple

example of solutions of that type. The solutions of Urusovskii [95] and Ivanov [99], based on the Malyuzhinets' method, with one monopole actuator surface and sound pressure and particle velocity detection, are related to this kind of source. However, because the detector-source combinations are always of MIMO type in the constructions according to the Malyuzhinets' method, no separate independent elements having a detector and an actuator part can be constructed based on that method.

In this work, a detailed description of a locally working JMC element is given, especially for planar applications in a three-dimensional space. Based on that, the principles of new three-unit approximations of a planar JMC element for a three-dimensional space are developed. The adaptive control system principle is introduced for a JMC element and its three-unit approximations.

The "four-unit JMC element" and the "three-unit approximations of the JMC element" are called the "four-element JMC element" and the "three-element approximations of the JMC element" in **Publication [III]**. Hopefully, changing the terminology clarifies the concepts.

1.6.3 JMC source configurations for waveguides

ANC in ducts is an important application field. One reason for the great interest in the active control of sound in ducts is that the sound field is one-dimensional at low frequencies, that is, sound propagates in two directions only, and the problem is thus relatively easy in principal. Another reason is that there exists a large amount of commercial applications of ANC in ducts, such as attenuation of noise in air-conditioning systems and in exhaust pipes of engines.

For true feedforward control to work, it is required that the actuator in the duct radiates only in the direction of sound propagation, i.e., downstream [125]. A principal problem in feedforward active noise control in waveguides is thus the acoustic feedback from the secondary source to the reference detector. A literature survey of various ways of suppressing this feedback is given in the Introduction of **Publication [IV]** and in more detail in the Introduction of **Publication [V]**, see also [126–134]. The most natural technique to suppress the acoustic feedback is the use of unidirectional actuators, unidirectional detectors, or

both simultaneously. Furthermore, with a unidirectional transducer, the control system can be kept relatively simple [135].

Because the JMC method is purely an exact field-theoretical approach to the problem of field reshaping, it always yields the optimum solution to any field reshaping problem. From this point of view it is a very natural starting point for unidirectional actuators.

All unidirectional actuator solutions for waveguides based on the JMC method are constructed of three monopole actuators, two of them forming an approximation for a dipole radiator [13–15, 18–20, 22, 24, 27, 36, 37, 42, 43, 48, 49, 73]. In one paper, a solution with a monopole and a "real dipolar source" is mentioned [27]. The adjustments of the inputs of the actuator elements, due to the approximation of the dipole by two monopoles, have not been presented in the references above, except in one by Mangiante, Mathevon and Roure [73].

There are no presentations of *two-element actuators* (of similar type) for waveguides that are based on the JMC method in the literature. For three-dimensional applications, Jessel and Angevine presented a source solution based on two monopoles, adjusted to give both the monopole and dipole radiation [40]. Proper amplitude and phase adjustments needed were not given, nor was it stated whether the system was of single-in tripole or tripole type. Apart from the JMC method, cardioidlike radiation patterns have been constructed by the same principle with two loudspeakers, see, e.g., [136], or with two microphones, see, e.g., [137, 138]. The proper amplitude filter functions to correct the approximations of the monopole and dipole parts of radiation are not given in those presentations (in fact, they are dependent on radiation direction in three-dimensional cases).

There are also other unidirectional two- and three-element solutions than those based on the JMC method, namely Swinbanks' solutions [139, 140], the solutions of Berengier and Roure [141], and the solution of La Fontaine and Shepherd [142], the last two being merely special cases of Swinbanks' solutions. There is one more solution to be introduced: the two-element "maximally efficient source" of Winkler and Elliott [135]. It refers to a source eliminating the total sound pressure downstream with the least "effort" [102]. The least effort signifies minimizing the square of the absolute values of the volume velocities

of the source complex. The maximally efficient source is not ideal because it is not unidirectional at low frequencies. All these solutions need inter-channel delays in their control systems. As will be presented in Section 2.3.6, the accurate realization of short delays requires much signal processing power. This fact makes the JMC-based solutions superior because they can be realized without inter-channel delays.

There are also unidirectional solutions with more than three elements. The Swinbanks' solutions [139] and the solutions of Berengier and Roure [141] can be readily generalized to multi-element versions. Other solutions are presented, e.g., in [143–145]. The purpose of using more than three actuators is to obtain better properties of the actuator system, e.g., wider frequency range and better low-frequency radiation properties.

In this work, as *new three-element solutions* in waveguides, one ideal source and four approximations are presented. In the three-element actuators, the novelty value is in introducing the expressions for the pertinent filter functions (equalization functions) of the actuator elements. In the paper of Mangiante, Mathevon and Roure, the filter functions are presented for an ideal solution [73], but the solution is of true tripole type differing from the single-in solution presented in this thesis. As *new two-element solutions*, one ideal source and six approximations are presented with three different inter-channel delays. The general way of approaching the monopole and dipole filter functions has made it possible to find many suboptimal approximate three- and two-element solutions, too, most of which have not been presented in the literature. Further, the adaptive JMC structures concerning the new ideal two-element solutions are presented.

The filter functions are called "weightings" in **Publications [IV]**, **[V]** and **[VI]**. The term "filter function" is used here instead, in order to distinguish it from "weight operator" or "weighting function" of the formulation of the JMC method.

2. Summary of the publications

2.1 Modified JMC method [I, II]

The modified JMC method and the concepts of vector and dyadic weighting, developed by the author, were first published in 1989 [54], and after that in two conferences, in 1990 **[I]** and in 1993 [64]. A thorough presentation is given in **Publication [II]**, and a shorter version in **Publication [III]** as an introduction to JMC elements.

In the modified JMC method, the primary sources remain unchanged while in the original JMC method they may be reshaped. The secondary sources needed generally in the modified JMC method are presented in equation (8) in **Publication [I]** and in equation (20) in **Publication [II]**. For the vector weighting in a flowless and homogeneous ideal fluid they are presented in equations (9) and (23) in respective publications, and for the dyadic weighting in similar conditions in equations (13) and (30) respectively. The vector-weighting factor weights the sound pressure and particle velocity independently, and further, the dyadic weighting factor weights the particle velocity causing its polarization [146] (or direction) to change.

By using the *vector weighting*, the ratio of the sound pressure and particle velocity, and the ratio of the active and reactive intensity can be changed into the desired values by using the secondary sources. The directions of the active and reactive intensity can be changed but only in the subspace spanned by the primary active and reactive intensity. The divergence and curl of the intensity can also be modified to some extent.

By using the *dyadic weighting*, the properties of the linear and second-order field quantities can be changed in quite an arbitrary way by using the secondary sources. Especially the intensity can be changed into the desired value, including modifications of the reactivity, direction, divergence and curl. The polarization (or direction in the case of a linear polarization) of the particle velocity can be changed arbitrarily.

A theoretical basis for general field modifications and optimization of secondary sources, based on the scalar, vector and dyadic weighting, has been presented. Requirements can be presented, e.g., for (a) the sound pressure and particle velocity amplitudes and phases, (b) the polarization of the particle velocity, (c) the direction and reactivity of the intensity and (d) the divergence and curl of the intensity. After setting the requirements, it is possible to define the weighting factor to obtain the desired field. When the weighting factor has been defined, the secondary source configuration needed to change the field to the desired one is uniquely defined. However, there are two important facts: Firstly, the exact form of the weighting factor is not always uniquely defined by the requirements but it must be selected from among the possibilities which give the desired field. Secondly, various quantities of the acoustic field are connected with each other by their mutual dependence, so arbitrary properties cannot be required of all quantities at the same time if the secondary sources are not wanted to exist everywhere in the space.

2.2 Planar JMC element and its three-unit approximations [III]

2.2.1 Planar JMC element

In the JMC method, three types of secondary source distributions are needed: monopoles, dipoles and quadripoles. The monopole distribution is determined by the normal component of the primary particle velocity, the dipole distribution by the primary sound pressure (scalar source determined by the vector field and vector source determined by the scalar field, as stated by Jessel [49]), and the quadripole distribution by the tangential component of the primary particle velocity at the planar surface of the element.

A JMC element is defined in **Publication [III]** as a combination of a detector and an actuator mounted near each other, both functioning locally according to the principle of the JMC method. If several JMC elements (according to the definition above) are working simultaneously, the basic control signal for every actuator is obtained from its own detector unit, the entity forming a multiple SISO system. By using several JMC elements, a closed surface around the noise sources or the controlled volume can be constructed. However, this is not al-

ways necessary: the JMC elements absorb sound energy locally also if they work separately without forming pure closed surfaces.

The principle of the JMC element is illustrated in Figure 4. The measured primary field quantities are the sound pressure (p), and the normal and tangential components of the particle velocity (u_x, u_T). The secondary source quantities are the surface monopole distribution (volume velocity per unit area, $q_s{''}$), the surface dipole distribution (force per unit area, $f_s{''}$) and the surface quadripole distribution ($g_s{''}$). The transfer functions of the detectors from acoustical field quantities to voltage units are H_1, H_2 and H_3, and the transfer functions of the actuator elements from voltage units to acoustical units are H_4, H_5 and H_6. The symbol V with different subscripts denotes different voltages in the control system. A detailed description of the detector and actuator units of the JMC element is given in Section 5 of **Publication [III]**. In the figure one can see that each detector type controls one actuator type; there are no "cross-connections" between the individual units in an ideal case with a time-independent weighting factor. In Jessel's presentation of the JMC element there are cross-connections, possibly for the sake of non-ideal constructions [16] (discussed later in Section 2.2.3).
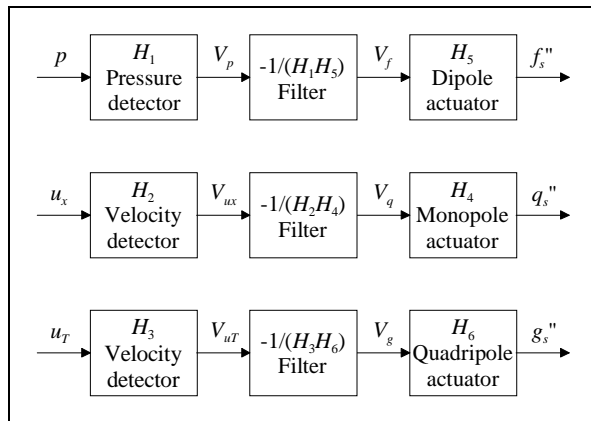

Figure 4. Principle of a JMC element.

With a multiple JMC element system, the tangential component of the particle velocity needs not to be measured: this information is included in the measured sound pressure data through the pressure gradient applied to the tangential direction. This means that the tangential particle velocity detectors are inherently

included in the group of the sound pressure detectors. Further, with a multiple JMC element system, the quadripole distribution is automatically generated by the dependence of the dipole distribution on the lateral coordinates. This can be seen with the help of equation (12) in **Publication [II]**. In the case of a multiple JMC element system, the last part of the JMC element (tangential velocity – quadripole) in Figure 4 can be omitted, for the reasons explained above. This solution is called a four-unit JMC element (two detector units and two actuator units).

2.2.2 Three-unit approximations of the JMC element

Based on the four-unit version of the JMC element, four approximations can be constructed by omitting one of the detector or actuator units. In the approximations, either one of the primary field quantities or one of the secondary source quantities is approximated by the other, through a field impedance function. The residual sound pressures (p_{res}) are minimized by controlling adaptively the actual impedance function (H_Z) or admittance function ($H_{1/Z}$) through a criterion. The JMC method places no special restrictions on the number or location of the residual microphones, nor for the criterion. The three-unit approximations are presented in Figure 5, Figure 6, Figure 7 and Figure 8 below. The solutions of Urusovskii [95] and Ivanov [99] may be categorized as MIMO versions of the approximation in Figure 6 with a fixed admittance function to be selected case by case. The three-unit approximations with one detector unit in Figure 7 and Figure 8 can be categorized as generalizations of a single-in tripole.

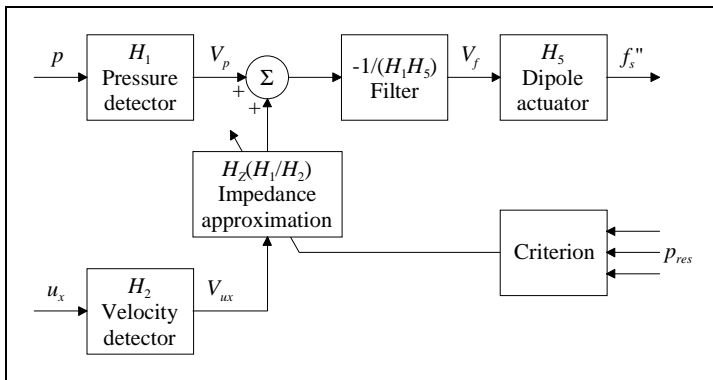*Figure 5. A three-unit approximation of the JMC element with two detectors and a dipole actuator.*
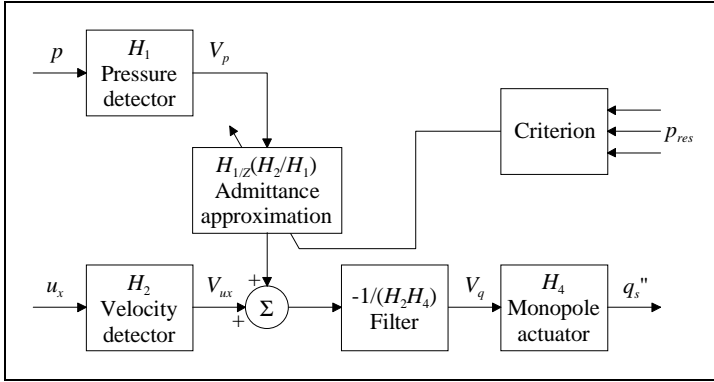
Figure 6. A three-unit approximation of the JMC element with two detectors and a monopole actuator.
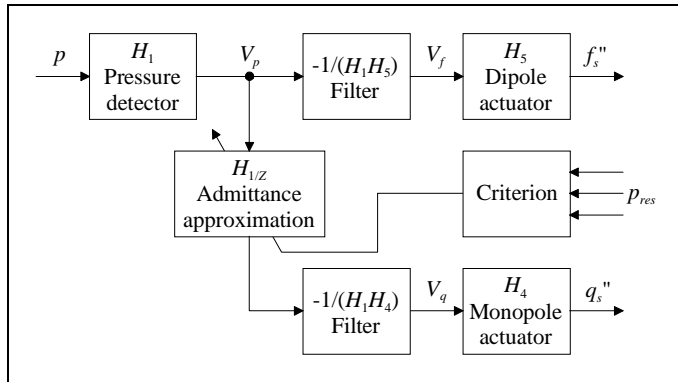

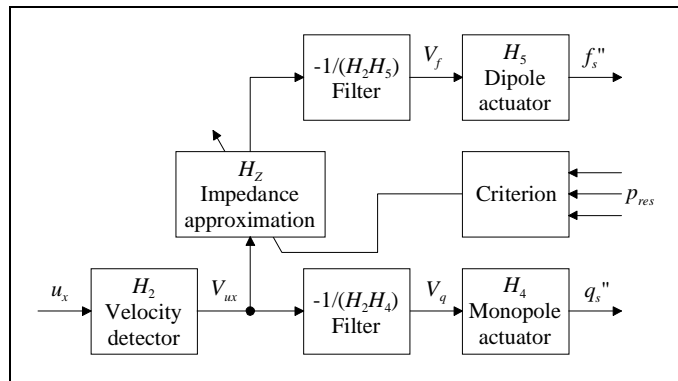*Figure 7. A three-unit approximation of the JMC element with a pressure detector and two actuators.*

Figure 8. A three-unit approximation of the JMC element with a velocity detector and two actuators.

2.2.3 Adaptive non-recursive control for JMC elements

A four-unit JMC element controlled by an adaptive multiple-channel filtered-x LMS algorithm [107] is shown in Figure 9. For the notations of the figure, see **Publication [III]**. The number of error signals (e_1, e_2, e_3) has been chosen to be three but it can be higher as well. With the three-unit approximations, the control system is quite similar, except that either only one detector is steering both actuators or both detectors are steering a common actuator.
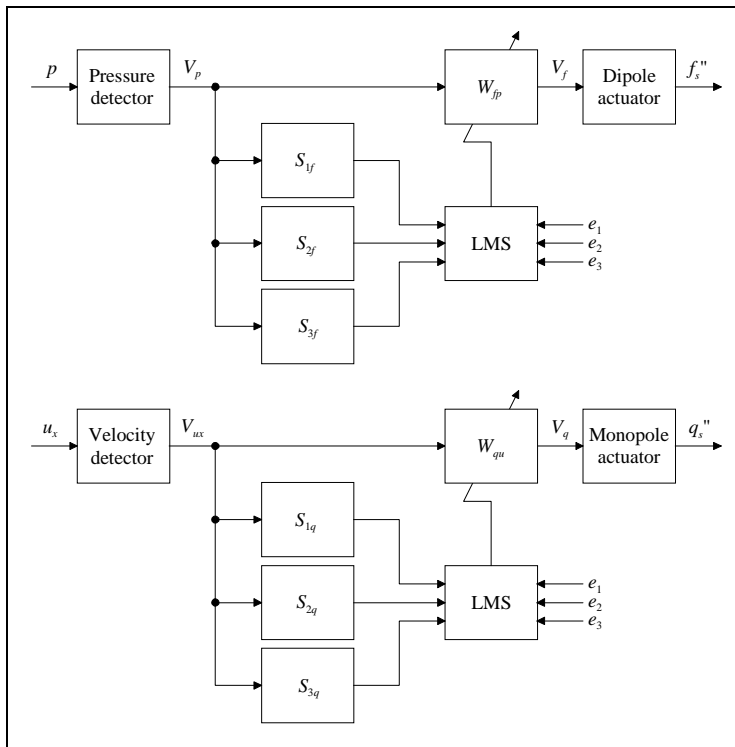
Figure 9. A four-unit JMC element controlled by an adaptive multiple-channel filtered-x LMS algorithm.

There may be a need for some distance between the detector and actuator part to get some propagation delay for the primary signal between the detector and the actuator, to get processing time for the filtered-x LMS algorithm. In the case where the distance is too large, there must be cross-connections in the control system between the various units of the JMC element and in some cases also

inter-element connections between the separate JMC elements, leading to MIMO control systems instead of multiple SISO ones.

2.3 JMC source configurations for waveguides [IV, V]

The ideal three- and two-element JMC sources for waveguides and their approximate solutions were first published in 1995–1996 by Uosukainen [70, 71], the inter-channel delay optimized only downstream with the two-element solutions. The ideal two-element solution with no inter-channel delay was presented also in 1997 [72]. Since then, the ideal solutions were presented in 1999 in **Publication [IV]** and in greater detail also in 1998 in **Publication [V]**, and the approximate solutions were presented in **Publication [V]**. In **Publications [IV]** and **[V]** the two-element solutions were presented with three possibilities of inter-channel delays.

The unidirectional systems to be described can be used for realizing reference detectors as well.

2.3.1 Basic constructions

The basic *three-element construction* to be examined consists of three actuator units of monopole type, as depicted in the upper part of Figure 10. The corresponding field and source quantities are presented in the lower part of Figure 10. The dipole units produce volume velocities q_1 and q_2 while the monopole unit produces volume velocity q_0. The quantity q_i in Figure 10 is the primary sound pressure p_i at $x = 0$ scaled to a volume velocity quantity. The sound is detected at $x = -L$ where the primary sound pressure scaled to volume velocity is q_L. Two delays are further introduced. The delay τ_L is the time the sound needs to propagate from the detector position to the middle of the actuator system (distance L). The delay τ corresponds to the acoustic propagation delay between the outermost monopoles forming the dipole approximation.

The basic *two-element construction* to be examined consists of two actuator units of monopole type, as depicted in Figure 11. The actuator units produce volume velocities q_1 and q_2, as in the lower part of Figure 10, without volume velocity q_0.
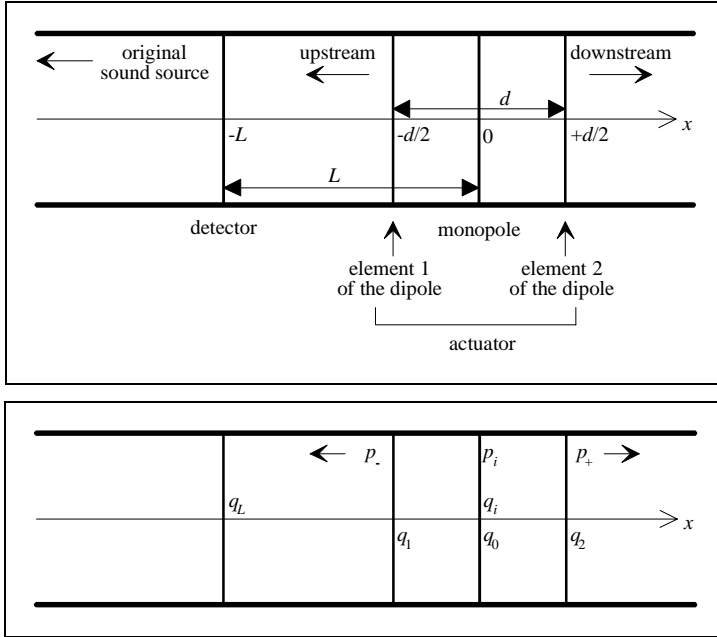
Figure 10. Schematic presentation of the geometry of the three-element actuator construction and the field and source quantities in a waveguide.

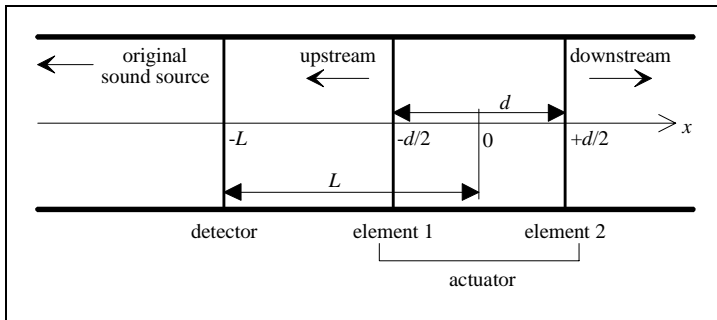*Figure 11. Schematic presentation of the geometry of the two-element actuator construction in a waveguide.*

2.3.2 Optimal three-element solution

Figure 12 shows the control system for the three-element structure. In the dipole signal, the integration ($\int$) is performed with respect to time (t).
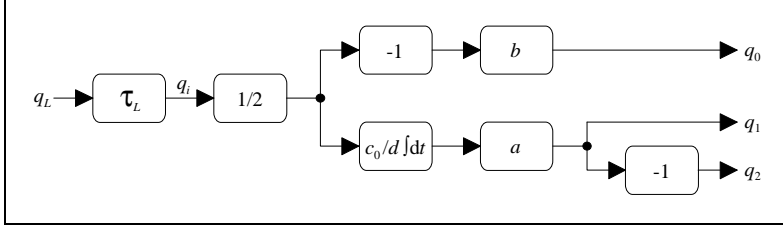
Figure 12. Control system of a modified three-element JMC actuator with an integrator in the dipole path.

At high frequencies the source configuration with unit filter functions does not work ideally, due to the approximated realization of the dipole part. That is why the monopole and the dipole are modified by frequency-dependent filter functions *b* and *a*, respectively, to compensate for the approximate character of the actuator. Since the approximation in the basic solution lies in the dipole part, proper modification of only the dipole part ($b = 1$) leads to the ideal solution where the residual sound pressures both down- and upstream vanish. The solution is

$$a = \frac{kd/2}{\sin(kd/2)}$$
$$b = 1 \; , \tag{1}$$

where *k* is the wave number.

2.3.3 Optimal two-element solutions

In two-element approximations of the JMC source, the volume velocities of both the monopole and dipole parts of radiation are approximately included in the two units, the total volume velocities q_1 and q_2 being thus combinations of the volume velocities of the approximated monopole and dipole parts of radiation.

The inter-channel delay, corresponding to the acoustic propagation delay between the actuator units, can be attached to the monopole part of the volume velocity q_2 with respect to that of the volume velocity q_1, to ensure that the monopole part of the radiation is correct *downstream*. The inter-channel delay can be selected also to ensure that the monopole part of the radiation is correct *upstream*. Another selection is the one having *no delays* in the monopole parts.

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Due to the approximated realizations of both the monopole and the dipole, they are modified by frequency-dependent filter functions *b* and *a*, respectively, as in the case of the three-element solutions. Figure 13, Figure 14 and Figure 15 show the control systems feeding the actuators when the inter-channel delay is optimized downstream, upstream, and when no inter-channel delay is used, respectively.

Figure 13. Control system of a two-element actuator with the inter-channel delay optimized downstream.
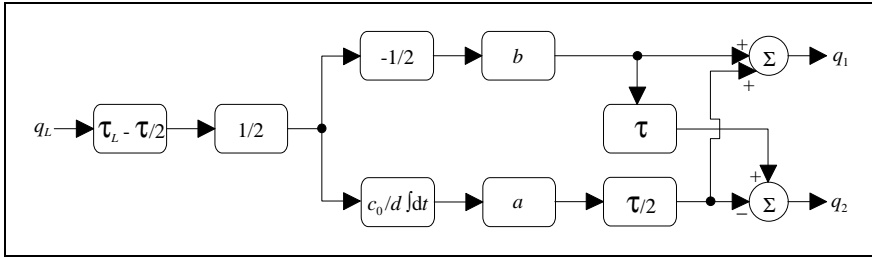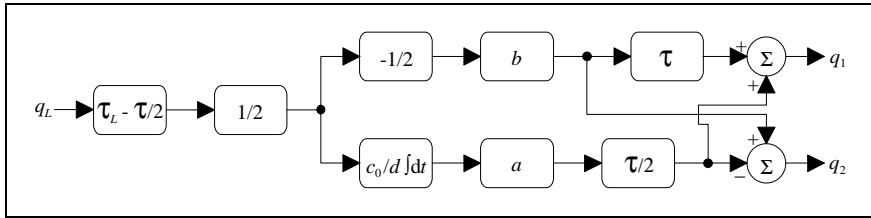

Figure 14. Control system of a two-element actuator with the inter-channel delay optimized upstream.
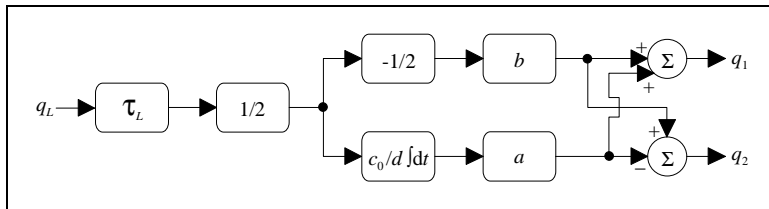

Figure 15. Control system of a two-element actuator with no inter-channel delay.

The optimal values for *a* and *b* are found by demanding that the sound pressure radiated by the actuator upstream and the residual sound pressure downstream vanish. The solution is

Delay optimized:	$a =$	$b =$
downstream	$\dfrac{\cos(kd)}{\cos^2(kd/2)}\dfrac{kd/2}{\sin(kd/2)}$	$\dfrac{1}{\cos^2(kd/2)}$
upstream	$\dfrac{1}{\cos^2(kd/2)}\dfrac{kd/2}{\sin(kd/2)}$	$\dfrac{1}{\cos^2(kd/2)}$
no delay	$\dfrac{kd/2}{\sin(kd/2)}$	$\dfrac{1}{\cos(kd/2)}$

$$(2)$$

The output volume velocities of all the three variations of the two-element Ideal Source are mutually identical, and the differences in the weighting functions compensate the effects of the different inter-channel delays. Furthermore, the volume velocities are identical with those of Swinbanks' two-element actuator [139] although the procedure of attaining them is quite different. The control system of Swinbanks' two-element actuator may seem simple in relation to those of the two-element Ideal Source, see Figure 5 of **Publication [IV]** or Figure 6 of **Publication [V]**. However, the delayless version of the two-element Ideal Source has the advantage of no phase shift between the volume velocities of the elements, which turns out to be advantageous in practical implementation of digital control systems.

2.3.4 Approximations

Besides the specific approximations presented in this section, in **Publication [V]** (Appendices A and B) there are presented the general relationships for the filter functions for three special cases: the radiation upstream or the total sound pressure downstream will not exceed a limiting value, and the case where there is a requirement for the ratio of the upstream and downstream sound pressures.

The different *approximate three-element solutions* are given in Table 1. The solutions have been given identifications *Approximations 1–4*.

The idea of Approximation 2 is a three-element generalization of the two-element maximally efficient source defined by Winkler and Elliott [135]. This

solution is not unidirectional at low frequencies. Approximations 3 and 4 are solutions where the dipole part is not modified ($a = 1$) and the monopole part is modified by eliminating totally either the upstream or downstream sound.

Table 1. Different approximations of the three-element actuator.

Solution	Illustration of solution
Appr. 1	Basic 3-element actuator, neither *a* nor *b* optimized
Appr. 2	Maximally efficient source, total sound downstream vanishes
Appr. 3	Dipole part not modified, no upstream radiation
Appr. 4	Dipole part not modified, total sound downstream vanishes

The filter functions and the residual sound pressures for the three-element approximations are presented in Table 2 and Table 3 in **Publication [V]**. Also graphical presentations are given there.

The different *approximate two-element solutions* are given in Table 2. The solutions have been given identifications *Approximations 5–10*. All the solutions in Table 2 can be realized with any of the three possibilities of the inter-channel delay.

Table 2. Different solutions for the two-element actuators.

Solution	Illustration of solution
Appr. 5	Basic two-element solution, neither *a* nor *b* optimized
Appr. 6	Maximally efficient source, total sound downstream vanishes
Appr. 7	Monopole part not modified, no upstream radiation
Appr. 8	Monopole part not modified, total sound downstream vanishes
Appr. 9	Dipole part not modified, no upstream radiation
Appr. 10	Dipole part not modified, total sound downstream vanishes

Approximation 6 with the inter-channel delay optimized downstream is the same as the maximally efficient source of Winkler and Elliott [135], so it is not

a new solution. However, Approximation 6 with the inter-channel delay optimized upstream or with no inter-channel delay is a new solution. Both of them are also called here maximally efficient sources (although they differ from the solution of Winkler and Elliott).

The filter functions and the residual sound pressures for the two-element approximations having different inter-channel delays are presented in Tables 5–10 in **Publication [V]**. Also graphical presentations are given there.

2.3.5 Continuous available frequency ranges

The continuous available frequency range, due to filter functions, is the frequency range from zero frequency to the first frequency where a filter function tends to infinite. The continuous available frequency range, due to residual sound pressures, is the frequency range from zero frequency to the first frequency above which the magnitude of the residual sound pressure up- or downstream is higher than that of the incoming sound pressure. In practice, the useful frequency ranges are narrower than these definitions suggest, due to non-idealities in practical control systems.

The upper frequency limit of the continuous available frequency range of the *three-element solutions* corresponds to the wavelength equal to distance d, except that Approximation 1 has no upper frequency limit (a practical limit is the same). The limits for continuous available frequency ranges for *two-element solutions* are gathered in Table 3. The dash (–) indicates that there is no upper limit.

2.3.6 Discussion of digital control

The main conclusions from the simulations in **Publications [IV]** and **[V]** concerning the digital control of the sources in waveguides are

1) the digital control systems can be reasonably realized with the new source configurations

Table 3. Upper frequency limits of continuous available frequency ranges of different two-element solutions for different inter-channel delays.

Solution	Highest available frequency d/λ when inter-channel delay optimized		
	downstream	upstream	no delay
Ideal	0.5	0.5	0.5
Appr. 5	–	0.39[*]	0.65
Appr. 6	–	–	–
Appr. 7	1	1	0.5
Appr. 8	1	1	0.5
Appr. 9	0.2[*]	–	0.5
Appr. 10	–	0.19[*]	0.5

[*] Not useful solutions

2) the two-element Ideal Source with inter-channel delay and the traditional Swinbanks' two-element source require a fractional delay filter for the inter-channel delay; this requires much signal processing power

3) sources without inter-channel delays, i.e., the three-element Ideal Source and the delayless two-element Ideal Source, need no fractional delay filters, so the control of those sources can be realized with reasonably low-order filters.

A review of fractional delay digital filter approximations is presented in [147], see also [148].

In a design example, with a requirement of 40 dB attenuation in a frequency range of 50 Hz – 900 Hz, an FIR filter of length 35 was needed in Swinbanks' two-element configuration while for the delayless two-element Ideal Source the length 11 was sufficient. The new two-element configurations without inter-channel delays are superior to all other traditional unidirectional two-element solutions, e.g., that of Swinbanks [139], Berengier and Roure [141], and La Fontaine and Shepherd [142].

2.4 Adaptive JMC structures in ducts [VI]

The adaptive signal processing structure shown in Figure 16 is based on the configuration of Swinbanks' method. The symbols are explained in **Publication [VI]**. Elliott also presented an adaptive signal processing structure for Swinbanks' source in 1993 [149].
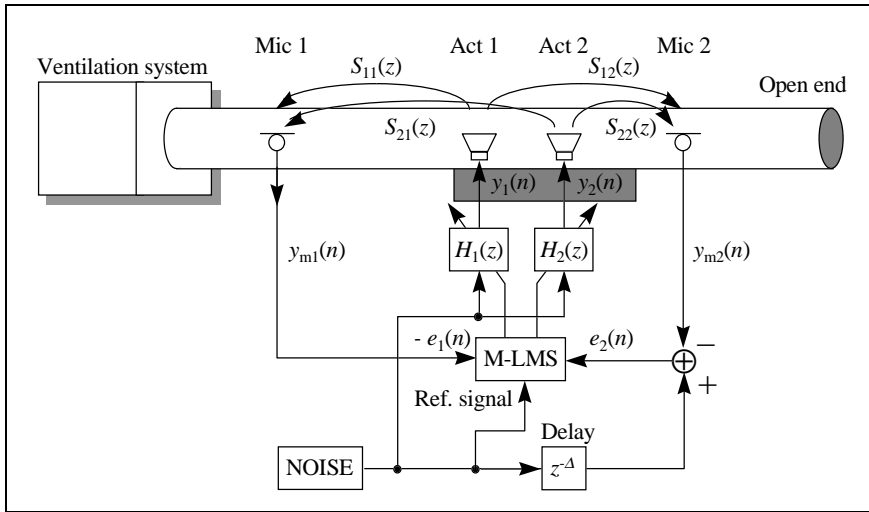
Figure 16. The adaptive signal processing structure for the automatic design of a unidirectional two-element actuator based on Swinbanks' method, in a calibration mode. The main application for this system is ANC in a ventilation duct, as sketched in the figure.

If the JMC-based approach is used, the shaded part in the middle of Figure 16 has to be substituted by the structures of Figure 17. The structures of these figures are based on the inter-channel delay optimization downstream according to Figure 13, upstream according to Figure 14, or no inter-channel delay according to Figure 15, respectively.

In the simulations of **Publication [VI]**, it was shown that the adaptive control system works well with Swinbanks' two-element structure. The same conclusion may be expected also with the JMC structures when the proper configuration changes above have been realized.
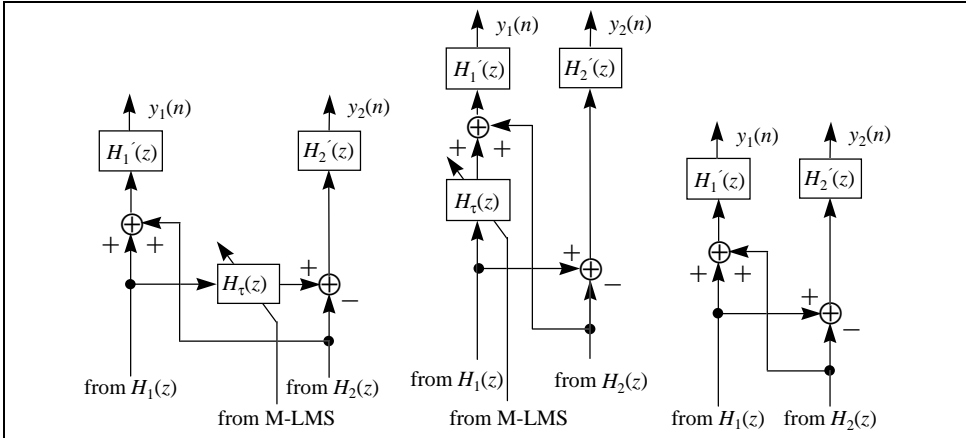
Figure 17. The shaded part of Figure 16, when the JMC-based configuration with inter-channel delay optimization downstream, upstream, or with no delay is used.

2.5 Contribution of the author

In **Publications [I]**, **[II]** and **[III]**, the basic ideas (modified JMC method, vector and dyadic weighting, three-unit approximations of the JMC element) are created by the author and the author has compiled all the results presented in those publications.

Publications [IV], **[V]** and **[VI]** are based on the co-operation of the author and Dr. Välimäki. In **Publications [IV]** and **[V]**, the author is responsible for the source configurations and their filter functions. In those publications, the co-author has presented the aspects concerning the digital control system, and all simulations have been done by him. In **Publication [VI]**, the author introduces the source configurations and the modifications needed in Swinbanks' adaptive solution to be changed into adaptive JMC solutions. In that publication, the co-author is otherwise responsible for the adaptive digital control systems.

3. Conclusions

3.1 Main results

The main results of this thesis may be summarized as follows:

Theoretical extensions:

1. A modified JMC method has been developed. The difference between the JMC method and the modified version of it is that in the latter the primary sources remain unchanged in all cases while in the former the weight operator affects the primary source strengths.

2. The vector and dyadic weighting factors have been defined. The vector-weighting factor weights the sound pressure and particle velocity independently, and further, the dyadic weighting factor weights the particle velocity so that its polarization (or direction) is changed.

3. The quadripole distribution, needed in the secondary source configurations of the JMC method, is automatically generated by the dependence of the dipole distribution on the lateral coordinates. Thus, in multi-source systems no quadripole radiators are needed (necessarily).

New JMC source configurations for a three-dimensional space:

4. Based on the four-unit version of the JMC element, four three-unit approximations have been developed by omitting one of the detector or actuator units. The approximations have either two detectors and one actuator, or one detector and two actuators. Either one of the primary field quantities or one of the secondary source quantities is approximated by the other, through a field impedance function.

New JMC source configurations for waveguides:

5. A realization for a new perfect unidirectional three-element actuator (the three-element Ideal Source) and four different ways to approximate it (Approximations 1–4), also new solutions, have been found.

6. One perfect unidirectional two-element configuration (the two-element Ideal Source) and six two-element approximations (5–10) have been discovered. Additionally, the inter-channel delay between the elements may be optimized so that (1) the monopole sound radiation is correct downstream or (2) it is correct upstream, or (3) there is no delay between the two channels. The three inter-channel delay optimization schemes offer 20 new two-element structures.

7. The delayless two-element Ideal Source needs no fractional delay filters, so the control of the source can be realized with reasonably low-order filters. This is valid for the three-element Ideal Source, too.

8. The adaptive JMC structures concerning the new ideal two-element solutions have been presented.

3.2 Scientific importance of the author's work

The results of this thesis enlarge possibilities in the active control of sound and facilitate more useful applications to be realized in ducts and three-dimensional spaces. The scientific importance of the author's work may be summarized as follows:

1. The modified JMC method makes field reshaping possible without affecting the primary sources, thus enlargening the possibilities of applying the JMC method in practical situations.

2. Possibilities in field reshaping have increased due to the introduction of the vector and dyadic weightings. The properties of the first and second-order field quantities can be changed in quite an arbitrary way with the help of the new weightings.

3. The new idea of the quadripole distributions in multi-source systems not needing to be separately realized clarifies the JMC theory and helps the practical implementation of the secondary sources in a three-dimensional case.

4. The new three-unit approximations of a planar JMC element for a three-dimensional space enable new possibilities in practical constructions of ANC devices. Especially the adaptive control of the field impedance function may open new aspects in the control systems of ANC.

5. The new three- and two-element ideal solutions and their approximations for waveguides offer several new possibilities in source configurations in ducts. Especially the possibility of constructing the control systems without any inter-channel delay enables the use of reasonably low-order filters in the control, leading to simplified control algorithms, reduced computing time and improved performance of ANC systems in ducts.

3.3 Future research

The JMC method extended to networks of systems according to the general system theory could give new possibilities, e.g., in taking into account psychoacoustical criteria in the active control of sound in a rigorous way.

In the JMC theory, the detectors and actuators are supposed to be acoustically transparent. This assumption may be valid with conventional transducers at low frequencies. However, the growing desire to use planar elements, e.g., flat film actuators, to obtain continuous and flat transducers, may lead to a different situation. It could be useful to develop the JMC theory to include nontransparent transducers.

The utilization of the JMC theory may give an opportunity to extend the scope of the active control of sound to many new application areas. One possibility could be variable acoustics in a concert hall or in a home theatre system, controlled by locally working independent JMC elements. The realization of that kind of elements may open new possibilities also in much simpler configura-

tions, e.g., in ANC applied to noise in transportation systems and environmental noise.

Future research in the area of unidirectional sources for waveguides will include practical implementation and measurements with the new actuator configurations. The combined use of a unidirectional actuator and a unidirectional detector seems to be an effective way to minimize the acoustic feedback in tube-acoustic ANC systems.

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