Noise-Induced Interference with Speech Communication: A Fuzzy Approach

Zaheeruddin
Department of Electrical Engineering
Faculty of Engineering and Technology
Jamia Millia Islamia (A Central University)
Jamia Nagar, New Delhi-110025
India
Zaheer_2k@hotmail.com

V. K. Jain
School of Environmental Sciences
Jawaharlal Nehru University
New Mehrauli Road, New Delhi-110067
India
Vkjo400@mail.jnu.ac.in

Abstract **– In this paper, an attempt has been made to develop a fuzzy model to investigate the effects of noise pollution on speech interference. The speech interference measured in terms of speech intelligibility is considered to be a function of noise level, distance between speaker and listener, and the age of the listener. The model has been implemented on Fuzzy Logic Toolbox of MATLAB using both Mamdani and Sugeno techniques. The model results are in good agreement with the survey findings of World Health Organization (WHO) and U.S. Environmental Protection Agency (EPA). The study reveals that for good communication at normal distances ('short' and 'medium') encountered in ambient environment, the noise level should not exceed 65 dB(A) for 'young' and 'middle aged', and 55 dB(A) for 'old' persons. The present effort also establishes the usefulness of fuzzy technique in studying the environmental problems where the cause-effect relationships are inherently fuzzy in nature.**

I. INTRODUCTION

Fuzzy set theory [1] provides a theoretical basis for dealing with the imprecision and uncertainty. Following the first paper, "Fuzzy Sets," in 1965 [1], Zadeh proposed a fuzzy algorithm [2] leading towards the idea of linguistic description of human thinking or decision making. The most remarkable paper related to fuzzy rule based system appeared in 1973 [3], in which Zadeh suggested a linguistic approach for modelling complex and ill-defined systems. Based on fuzzy set theory, fuzzy expert systems [4] have now been successfully applied to a wide range of real-world problems. Basically, a fuzzy rule-based system provides an effective way to capture the approximate and inexact nature of the real world. In particular, fuzzy rule-based systems have been found to be most effective when the problems are too complex for analysis by conventional quantitative techniques or when the available information from the problems is qualitative, inexact, incomplete, imprecise, or uncertain.

One such problem frequently encountered is that of noise induced interference with speech communication in urban and industrial environments. For example, noise can disrupt face-to-face and telephone conversation, and the enjoyment of radio and television in the home [5,6]. It can also disrupt effective communication between teachers and pupils in schools close to airports [7]. Aviation safety [8] in hundreds of accident investigations reported the use of same words "say again" exchanged between pilots and controllers.

In order to model the noise induced interference, speech intelligibility can be considered as a function of several parameters. Since the cause-effect relationship of noise on human being is highly complex, uncertain, and non-linear in nature, it is quite difficult to properly model it by conventional methods. In the present paper, an attempt has been made to model this cause-effect relationship of noise with speech interference using fuzzy approach. A brief literature survey on noise interference with speech communication is given in Section II. In Section III, the basic concepts of fuzzy models are discussed. The methodology for its development and implementation details is presented in Section IV. Results are discussed in Section V followed by conclusions in Section VI.

II. SPEECH INTERFERENCE

Noise interference with speech communication is basically a masking process in which simultaneous, interfering noise renders speech incapable of being understood [5]. This masking process can cause anything from a slight irritation to a serious safety hazard involving an accident or even a fatality because of the failure to hear the warning sounds of imminent danger. Noise may also mask many other acoustical signals important for daily life, such as doorbells, telephone signals, alarm clocks, fire alarms and other warning signals, and music [9].

The masking effect of noise on speech communication is generally evaluated in terms of speech intelligibility, which includes words, message, and sentence intelligibility. Speech intelligibility is an indication of how well speech is recognized and is defined as the proportion of spoken messages, which are correctly understood [10,11]. For complete sentence intelligibility in listeners with normal hearing, the signal-to-noise ratio (i.e. the difference between the speech level and the sound pressure level of the interfering noise) should be 15–18 dB(A) [12]. When the speech level is equal to the noise level, intelligibility falls to 95%. Because of the redundancy of speech, 95% intelligibility usually permits reliable although not necessarily comfortable conversation [13,14].

Many factors contribute to the effects of noise on communication interference. The most important are noise levels, distance between speaker and listener, and age. The degree of interference of noise with speech depends on noise level in relation to the level that conveys the desired information. The higher the level of the masking noise, the greater will be the percentage of speech sounds that become incomprehensible to the listener [15]. As the sound pressure level of an interfering noise increases, people automatically raise their voice to overcome the masking effect upon speech (increase of vocal effort). For example, in quiet surroundings, the speech level at 1 m distance averages 45–50 dB(A) but is 30 dB(A) higher when shouting [5]. EPA [16] recommendations suggested that sound pressure levels as high as 45 dB(A) would be acceptable. With raised voice (increased vocal effort) sentences may be 100% intelligible for noise levels of up to 55 dB(A) and sentences spoken with straining vocal effort can be 100% intelligible with noise levels of about 65 dB(A). Normal speech communication becomes impossible at about 75 dB(A) [5,17].

It has also been reported that for outdoor conditions at a distance of 1 m from the speaker, relaxed conversation occurs at a voice level of approximately 54-56 dB(A) and normal and raised voices at levels of approximately 60 and 66 dB(A) [10]. A summary of normal and raised voice levels for outdoor conditions at different distances from the speaker can be found in [5].

Another factor influencing communication interference is the age of the people involved [18-20]. Specifically, because children have poorer articulation skills than adults, "their lack of vocabulary or different concepts of the rules of language may render speech unintelligible when some of the cues in the speech stream are lost" [15]. Thus, noisy conditions are more likely to interfere with the speech of children than with that of adults [21,22]. Additionally, the ability to understand partially masked speech appears to begin deteriorating at around the age of 30. Thus, "the older the listener, the lower the background noise must be for practical or satisfactory communication" [15].

There are several other factors having less significant effects on noise-induced speech interference. For example, speech communication is affected also by the reverberation characteristics of the room [23,24]. Longer reverberation times make speech perception more difficult. The masking effect of interfering noise in speech discrimination is more pronounced for hearing-impaired persons than for persons with normal hearing [19,21]. Lower noise levels may be required, if the speaker does not enunciate clearly or if the speaker and the listener use different dialects [5]. In addition, speech content is also important, since a person that is trying to convey personal information is less likely to raise his or her voice to compensate for background noise. As a result, personal information is less likely to be understood. This also relates to another influencing factor, culture, which governs how close two people can be to each other. Spatial factors also contribute to communication interference, in that noises that are produced in areas containing highly reverberant materials become less localized, resulting in greater interference with communication [15]. Further, situational factors are also important in their influence on message predictability. That is, predictable messages can often be understood despite highly noisy backgrounds whereas less predictable messages are more poorly understood such as speech about unexpected situations that firemen encounter during a fire [15].

III. FUZZY MODELLING

The concept of fuzzy modelling was originally proposed by Zadeh [1] and developed further by other researchers [25-29]. Fuzzy models in a broad sense are of two types. The first category of the model proposed by Mamdani [30] is based on the collections of IF-THEN rules with both fuzzy antecedent and consequent predicates. The advantage of this model is that the rule base is generally provided by an expert. Hence to a certain degree it is transparent to interpretation and analysis. The second category of the fuzzy model is based on Takagi-Sugeno-Kang (TSK) method of reasoning [31]. These models are formed by IF-THEN rules that have a fuzzy antecedent part and functional consequent; essentially they are a combination of fuzzy and non-fuzzy models. The main advantage of this model is its computational efficiency [32].

The main paradigm of fuzzy model is that the fuzzy algorithm is a knowledge-based algorithm, the essential concepts of which are derived from fuzzy logic. The fuzzy system is an expert knowledge-based system that contains the fuzzy algorithm in a simple rule-base. As depicted in Fig. 1, a fuzzy system is composed of four parts: fuzzifier, knowledge base, inference engine, and defuzzifier. The fuzzifier converts real valued inputs into fuzzy values. The knowledge base includes fuzzy rule base and database. Membership functions of the linguistic terms are contained in the database. The inference engine calculates fuzzy output from fuzzy inputs using fuzzy implication function and finally the defuzzifier yields a real-value output from the inferred fuzzy output [33].

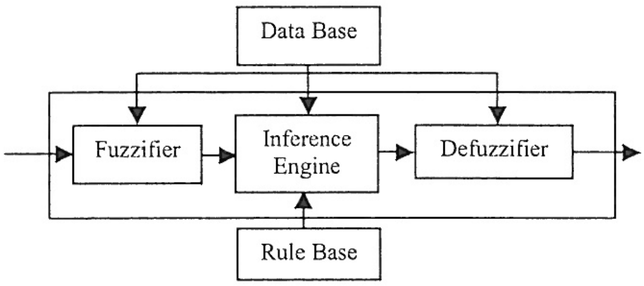

Fig. 1. Structure of fuzzy rule based systems

A typical rule is of the form:

IF antecedent THEN consequent

Depending on the form of the antecedent and consequent, this rule takes on forms ranging from very simple to complex. In general, a fuzzy model with multi-input multi-output (MIMO) system can be represented by the fuzzy if-then rules connected by the AND operator with multi-antecedent and multi-consequent variables (with r antecedents, s consequents, and n rules) as [28]:

IF U_1 is B_{11} **AND** U_2 is B_{12} **AND … AND** U_r is B_{1r}
THEN V_1 is D_{11} **AND** V_2 is D_{12} **AND … AND** V_s is D_{1s}
ALSO
…..
ALSO
IF U_1 is B_{m1} **AND** U_2 is B_{m2} **AND … AND** U_r is B_{mr}
THEN V_1 is D_{m1} **AND** V_2 is D_{m2} **AND … AND** V_s is D_{ms}

where $U_1, U_2, \ldots, U_r$ are the input variables and $V_1, V_2, \ldots, V_s$ are the output variables, Bij ($i = 1, \ldots, m$, $j = 1, \ldots, r$) and D_{ik} ($i = 1, \ldots, m$, $k = 1, \ldots, s$) are fuzzy subsets of the universes of discourse $X_1, X_2, \ldots, X_r$, and $Y_1, Y_2, \ldots, Y_s$ of $U_1, U_2, \ldots, U_r$ and $V_1, V_2, \ldots, V_s$ respectively. Conceptually, a system with multiple independent outputs can be partitioned into several groups of single output systems. Hence, a MIMO fuzzy system can be decomposed to a collection of several multi-inputs single-output (MISO). Therefore, in a system with s outputs, each multi-consequent rule is broken into s single-consequent rules. Though, the decomposition of MIMO fuzzy systems into MISO systems increases the number of rules, the representation of complex systems and hence modelling and inference would be more straightforward and simple. If the outputs V_1, V_2, ..., V_s are independent variables, then the MIMO system can be decomposed to a collection of s MISO system as:

IF U_1 is B_{i1} **AND** U_2 is B_{i2} **AND … AND** U_r is B_r
THEN V_1 is D_1
ALSO
…..
ALSO
IF U_1 is B_{i1} **AND** U_2 is B_{i2} **AND … AND** U_r is B_r
THEN V_s is D_s, $i = (1, m)$

IV. METHODOLOGY

Step 1: Identification of input and output variables:

The present fuzzy system has three inputs and one output as shown in Fig. 2. Only those inputs, which affect the output to a large extent, have been selected. The most important input variables are noise levels, distance, and age.

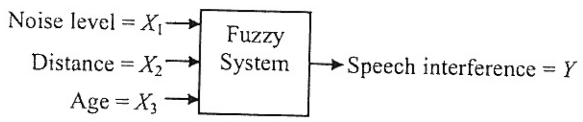

Fig. 2. Inputs and output of the system

Step 2: Selection of input and output variables:

The inputs and output with their linguistic values and fuzzy intervals are shown in TABLE I.

TABLE I

INPUTS AND OUTPUT WITH THEIR FUZZY VALUES AND FUZZY INTERVALS

System's Variables	Linguistic Variables	Linguistic Values	Fuzzy Intervals
Inputs	Noise Level	Low	45-55 dB(A)
		Medium low	50-60 dB(A)
		Medium	55-65 dB(A)
		Medium high	60-70 dB(A)
		High	65-75 dB(A)
		Very high	70-80 dB(A)
	Distance	Short	1-2.5 meters
		Medium	2-3.5 meters
		Long	3-5 meters
	Age	Young	10-40 years
		Middle aged	30-60 years
		Old	50-80 years
Output	Sentence intelligibility	Negligible	0-20 %
		Slight	10-40 %
		Moderate	30-70 %
		High	60-90 %
		Very high	80-100 %

Step 3: Determination of the membership functions for various input and output variables:

Linguistic values are expressed in the form of fuzzy sets. A fuzzy set is usually defined by its membership functions. As a sample case, the membership functions for one input are shown in Fig. 3.

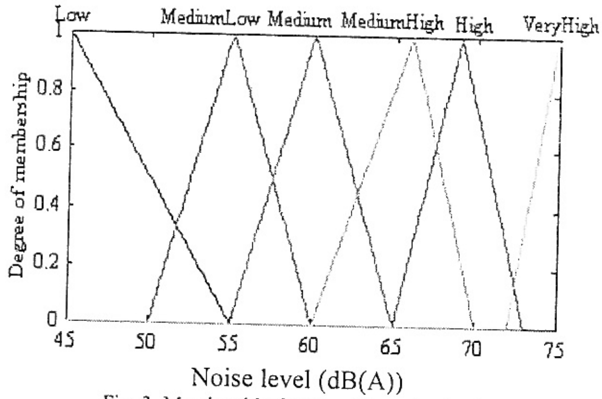

Fig. 3. Membership functions for noise levels

Step 4: Formation of the set of IF-THEN rules

The relationships between inputs and output are represented in the form of IF-THEN rules. As an illustration, one rule for each approach along-with their graphic representation has been given in Figs. 4(a) and (b) respectively.

Rule: IF noise level is "high" AND distance is "medium" AND person is "young" THEN sentence intelligibility is "good".

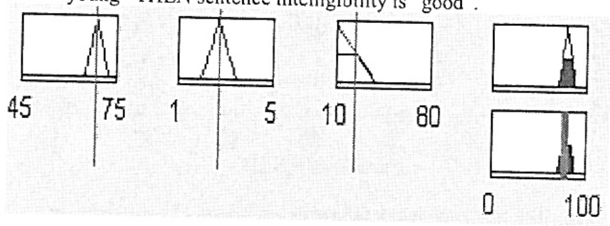

Fig. 4(a). Typical rule and their graphic representations in Mamdani approach

Rule: IF noise level is "high" AND distance is "medium" AND person is "young" THEN sentence intelligibility is "80%".

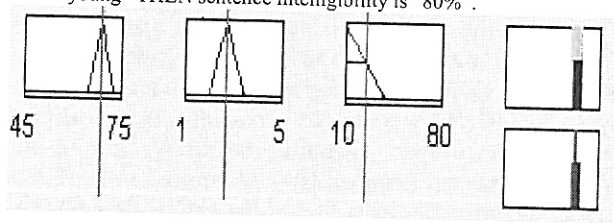

Fig. 4(b). Typical rule and their graphic representations in TSK approach

V. RESULTS AND DISCUSSION

Speech interference in the present model has been computed as a function of noise level with distance between speaker and listener, and the age of the listener as input parameters. The model has been implemented on Fuzzy Logic Toolbox of MATLAB® [34] using both Mamdani and Sugeno inference techniques, which yield similar results. The results have been obtained in the form of graphs with distance or age as parameters. For the sake of reference, only two graphs representing the speech interference as a function of noise level for 'short' and 'long' distances with different ages have been shown in Figs. 5(a) and (b).

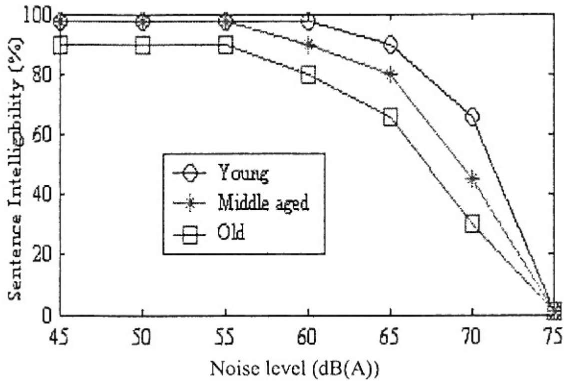

Fig. 5(a). Sentence intelligibility as a function of noise level for short distance with age as parameter

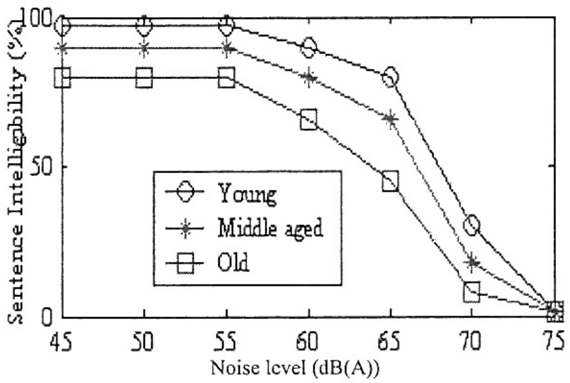

Fig. 5(b). Sentence intelligibility as a function of noise level for long distance with age as parameter

An examination of Fig. 5(a) shows that the sentence intelligibility remains unaffected up to the noise level of 55 dB(A) if the person is 'young' or 'middle aged' and the distance between speaker and listener is 'short'. However, it reduces as the noise level increases and approaches to 'almost zero ('worst')' at 75 dB(A). It is evident that the reduction in sentence intelligibility is gradual in noise interval 55—65 dB(A) and quite pronounced across all age groups for noise levels exceeding 65 dB(A). It is to be noted that due to presbycusis conditions (*Presbycusis* refers to the normal hearing loss of the elderly person), the sentence intelligibility of an 'old' person is never 'excellent' even at 'low' noise level. It is 'excellent (97.326%)', 'very good (90%)', and 'good (80%)' at 60 dB(A) for 'young', 'middle aged', and 'old' persons respectively. An increase of 5 dB(A) (i.e. at 65 dB(A)) changes its values to 'very good', 'good', and 'fair (65.3%)' for these categories of persons respectively. A further increase of 5 dB(A) (i.e. at 70 dB(A)) reduces its values sharply to 'fair', 'satisfactory (45%)', and 'acceptable (30%)' respectively. In contrast, for 'long' distance, appreciable deterioration in sentence intelligibility is observed for 'middle aged' and 'old' persons even at 65 dB(A) and for all age groups including the 'young' at 70 dB(A) as shown in Fig. 5(b). For example, at 70 dB(A), sentence intelligibility is 30%, 17.5%, and 8% for 'young', 'middle aged' and 'old' persons respectively.

In order to validate our present model, a comparison has been made in TABLE II between the model predictions and the findings from field surveys carried out in different parts of the world [5,6]. TABLE II shows the percentage of sentence intelligibility as a function of noise levels for 'short' and 'medium' distances. A comparison of model results for 'short' distance has been made with the survey findings specific to a typical living room [5] as it is reasonable to expect the distance between the speaker and listener to be in the fuzzy interval 1-2.5 meters. However, for medium distance (2-3.5 meters), the model results have been compared with the findings of outdoor surveys [6]. It may be pointed out the outdoor survey results are for distances greater than 2 meters. An examination of TABLE II clearly confirms the adequacy of the model in predicting the percentage of sentence intelligibility with noise levels at 'short' and 'medium' distances for 'young' persons.

TABLE II

A COMPARISON OF MODEL RESULTS WITH THE FINDINGS OF SURVEYS FOR HEALTHY YOUNG PERSONS

S. No.	Noise levels (dB(A))	Sentence Intelligibility					
		For short distance			For medium distance		
		Findings of U.S. EPA*(%)	Model results		Findings of U.S. EPA+(%)	Model results	
			Numerical value(%)	Fuzzy value		Numerical value(%)	Fuzzy value
1.	45	100	97.33	Excellent	100	97.33	Excellent
2.	50	100	97.33	Excellent	100	97.33	Excellent
3.	55	99	97.33	Excellent	98	97.33	Excellent
4.	60	98	97.33	Excellent	96.5	97.33	Excellent
5.	65	92	90	Very good	91	90	Very good
6.	70	65	65.3	Fair	47	45	Satisfactory
7.	75	0	0.875	Worst	0	0.875	Worst

*Source: Reference [5]
+Source: Reference [6]

VI. CONCLUSIONS

The present fuzzy model has been developed to investigate the effects of noise pollution on speech interference. The speech interference measured in terms of sentence intelligibility has been modelled as a function of noise levels, distance between the speaker and the listener, and the age of the person concerned. The model has been implemented on Fuzzy Logic Toolbox of MATLAB. The results obtained from the proposed model are in good agreement with the findings of field surveys conducted in different parts of the world. It is born out from the present study that for good communication at normal distances ('short' and 'medium') encountered in ambient environment, the noise level should not exceed 65 dB(A) for 'young' and 'middle aged' persons, and 55 dB(A) for 'old' persons. The present effort also establishes the usefulness of the fuzzy technique in studying the environmental problems where the cause-effect relationships are inherently fuzzy in nature.

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